ICAP 2012

The 23rd International Conference on Atomic Physics

23-27 July 2012

Palaiseau - France

Book of Abstracts

Web of Conferences

Foreword

The 23rd International Conference on Atomic Physics takes place in Ecole Polytechnique, a high level graduate school close to Paris.

Following the tradition of ICAP, the conference presents an outstanding programme of invited speakers covering the most recent subjects in the field of atomic physics, such as:

- Ultracold gases and Bose Einstein condensates,
- Ultracold Fermi gases,
- Fundamental atomic tests and measurements,
- Precision measurements, atomic clocks and interferometers,
- Quantum information and simulations with atoms and ions,
- Quantum optics and cavity QED with atoms,
- Atoms and molecules in optical lattices,
- From two-body to many-body systems,
- Ultrafast phenomena and free electron lasers,
- Beyond atomic physics (biophysics, optomechanics...).

The program includes 31 invited talks and 13 'hot topic' talks.

This book of abstracts gathers the contributions of these talks and of all posters, organized in three sessions.

The proceedings of the conference will be published online in open access by the "European Physical Journal Web of Conferences", http://www.epj-conferences.org/

On behalf of the committees, we would like to welcome you in Palaiseau, and to wish you an exciting conference.

Committees

Programme committee

Alain Aspect	France	Michèle Leduc	France
Hans Bachor	Australia	Maciej Lewenstein	Spain
Vanderlei Bagnato	Brazil	Anne L'Huillier	Sweden
Victor Balykin	Russia	Luis Orozco	USA
Rainer Blatt	Austria	Jian-Wei Pan	China
Denise Caldwell	USA	Hélène Perrin	France
Gordon Drake	Canada	Monika Ritsch-Marte	Austria
Wolfgang Ertmer	Germany	Sandro Stringari	Italy
Peter Hannaford	Australia	Regina de Vivie-Riedle	Germany
Philippe Grangier	France	Vladan Vuletic	USA
Massimo Inguscio	Italy	Ian Walmsley	UK
Hidetoshi Katori	Japan	Jun Ye	USA

Local organizing committee

Philippe Grangier (co-chair)	Institut d'Optique - CNRS
Michèle Leduc (co-chair)	ENS - CNRS
Hélène Perrin (co-chair)	U. Paris 13 - CNRS
Françoise Tarquis (secretary)	IFRAF - ENS
Serena Bastiani-Ceccotti	École Polytechnique - CNRS
Frédéric Chevy	ENS - LKB
Anna da Costa	Triangle de la Physique
Jean Dalibard	ENS - CNRS
Olivier Dulieu	U. Paris Sud - CNRS
Samuel Guibal	U. Paris 7 - CNRS
Jean-Claude Mialocq	CEA
François Ozanam	École Polytechnique - CNRS
Guillaume Petite	École Polytechnique - CEA
Denys Robert	École Polytechnique
Chris Westbrook	Institut d'Optique - CNRS

International advisory committee

Ennio Arimondo	Italy
Hans Bachor	Australia
Vanderlei Bagnato	Brazil
Viktor Balykin	Russia
Rainer Blatt	Austria
Claude Cohen-Tannoudji	France
Robin Côté	USA
Gordon Drake	Canada
Norval Fortson	USA
Theodor Hänsch	Germany
Peter Hannaford	Australia
Serge Haroche	France
Ed Hinds	UK
Massimo Inguscio	Italy
Wolfgang Ketterle	USA
Daniel Kleppner	USA
William Phillips	USA
Lev Pitaevskii	Russia
David Pritchard	USA
Fujio Shimizu	Japan
Winthrop Smith	USA
Jook Walraven	The Netherlands
David Wineland	USA
Tsutomu Yabuzaki	Japan
Mingsheng Zhan	China

Sponsors

Exhibitors

APS physics

Cambridge University Press

edp sciences

EPJ.org

IOP Publishing

M Squared

Office de Tourisme de Massy

MPB Communications Inc.

NKT Photonics
the power of light

Nufern

Optoprim

Oxford University Press

IDIL Fibres Optiques

Schäfter+Kirchhoff GmbH
OPTICS, METROLOGY, AND PHOTONICS

Springer

World Scientific
Connecting Great Minds

Quantel

HORIBA Scientific

MenloSystems

rofin
ROFIN-BAASEL FRANCE

Amplitude Technologies

Opton Laser International

Toptica Photonics

Table of contents

Monday 23 July, 9.15am-9.30am

Monday 23 July, 9.30am-11.15am

Monday 23 July, 2.45pm-4.30pm

Monday 23 July, 5.00pm-6.45pm

Tuesday 24 July, 9.15am-11am

Precision measurements, atomic clocks and interferometers

Precision metrology and many-body quantum physics (p. 37)
Jun Ye (45 min)

A gravitational wave observatory operating beyond the quantum shot-noise limit: squeezed light in application (p. 38)
Roman Schnabel (30 min)

Building a metrological toolbox for harnessing atoms and molecules (p. 38)
Paolo De Natale (30 min)

Tuesday 24 July, 2.45pm-4.30pm

Quantum information and quantum simulations

Quantum networks of atoms (p. 39)
Christopher Monroe (45 min)

Towards large-scale entanglement in a string of trapped ions (p. 39)
Benjamin Lanyon (30 min)

Quantum dynamics of a mobile single-spin impurity in an optical lattice (p. 40)
Stefan Kuhr (30 min)

Tuesday 24 July, 4.30pm-5.30pm

Hot topics (20 min each)

Progress towards measuring the electron EDM with thorium monoxide (p. 40)
John Doyle

Accurate determination of the Boltzmann constant by Doppler spectroscopy: towards a new definition of the Kelvin (p. 41)
Benoît Darquié

Frequency metrology in quantum degenerate helium (p. 41)
Wim Vassen

Wednesday 25 July, 9.15am-11.00am

Quantum optics and cavity QED

Cavity Quantum Electrodynamics with real and artificial atoms (p. 42)
Serge Haroche (45 min)

Quantum network with individual atoms and photons (p. 42)
Gerhard Rempe (30 min)

Cavity QED and quantum optics with a single quantum dot in a photonic crystal cavity or a photonic molecule (p. 43)
Jelena Vuckovic (30 min)

Wednesday 25 July, 11.30am-12.50am

Hot topics (20 min each)

Quantum storage and manipulation using gradient echo memory (p. 43)
Ping Koy Lam

Tunable gauge potential for spinless particles in driven lattices (p. 44)
Juliette Simonet

A superradiant laser with <1 intracavity photon (p. 44)
James Thompson

Interaction-based spin measurements in a cold atomic ensemble (p. 45)
Morgan Mitchell

Thursday 26 July, 9.15am-11.00am

Atoms and molecules in optical lattices

Exploring and controlling quantum gases under extreme conditions (p. 45)
Immanuel Bloch (45 min)

Altered interactions in artificial gauge fields (p. 46)
Ian Spielman (30 min)

Transport of impurities in optical lattices (p. 46)
Dieter Jaksch (30 min)

Thursday 26 July, 2.45pm-4.30pm

Many body physics

Three universal trimers in ultracold atoms (p. 47)
Masahito Ueda (45 min)

Tunable, deterministic few-fermion quantum systems (p. 47)
Selim Jochim (30 min)

New physics with dipolar gases (p. 48)
Gora Shlyapnikov (30 min)

Thursday 26 July, 5.00pm-6.00pm

Hot topics (20 min each)

Quantum degenerate Bose and Fermi dipolar gases of dysprosium realized (p. 48)
Benjamin Lev

Bose-Einstein condensation of erbium (p. 49)
Francesca Ferlaino

Spin and density response of strongly interacting Fermi gases (p. 49)
Chris Vale

Friday 27 July, 9.15am-11.00am

Ultrafast phenomena

Atomic physics with attosecond pulses (p. 50)
Anne L'Huillier (45 min)

Dynamics of electron wavepacket following tunnel ionization (p. 50)
Alexandra Landsman (30 min)

Ultrafast AMO physics at the LCLS X-ray FEL (p. 51)
Philip Bucksbaum (30 min)

Friday 27 July, 11.30am-12.15am

Beyond atomic physics

Quantum interfaces: from ultra-cold atoms to solid-state systems (p. 51)
Mikhail Lukin (45 min)

Friday 27 July, 2.00pm-3.30pm

Beyond atomic physics

Single molecule nanometry for biological physics (p. 52)
Taekjip Ha (30 min)

Quantum coherent coupling of light and mechanical motion (p. 52)
Tobias Kippenberg (30 min)

Theory and experiments with quantum fluids of light (p. 53)
Iacopo Carusotto (30 min)

Friday 27 July, 4.00pm-5.00pm

Hot topics (20 min each)

Attosecond control of collective charges in plasmas (p. 53)
Antonin Borot

Hybrid atom-membrane optomechanics (p. 54)
Philipp Treutlein

Feedback in a cavity QED system for control of quantum beats (p. 54)
Luis Orozco

Posters sessions

Monday 23 July, 11.00am-2.45pm

Topic A - Precision measurements

01- Atom interferometry

02- Atomic clocks

15- Precision measurements and tests of fundamental physics

Topic A - Precision measurements

19- Spectroscopy

Topic B - Ultracold gases

06- Bose gases

Topic B - Ultracold gases

09- Dipolar gases

10- Fermi gases

13- Optical lattices

Topic C - Quantum

16- Quantum information

17- Quantum optics and cavity QED

18- Quantum simulators with atoms and ions

Topic D - Traps & Interactions

03- Atomic interactions and collisions

07- Cold neutral molecules and ionic molecules, cold chemistry

08- Cooling and trapping of atoms and ions

Topic D - Traps & Interactions

11- From two body to manybody systems

Topic E - Atomic physics and beyond

04- Atoms in external fields

05- Beyond atomic physics

12- Intense fields and ultrafast phenomena

14- Other

Tuesday 24 July, 11.00am-2.45pm

Topic A - Precision measurements

Topic B - Ultracold gases

06- Bose gases

09- Dipolar gases

Topic B - Ultracold gases

10- Fermi gases

13- Optical lattices

Topic C - Quantum

16- Quantum information

Topic C - Quantum

17- Quantum optics and cavity QED

18- Quantum simulators with atoms and ions

Topic D - Traps & Interactions

03- Atomic interactions and collisions

Topic D - Traps & Interactions

07- Cold neutral and ionic molecules, cold chemistry

08- Cooling and trapping of atoms and ions

11- From two body to manybody systems

Topic E - Atomic physics and beyond

04- Atoms in external fields

05- Beyond atomic physics (bio, optomechanics, astro, etc.)

Topic E - Atomic physics and beyond

12- Intense fields and ultrafast phenomena

14- Other

Thursday 26 July, 11.00am-2.45pm

Topic A - Precision measurements

01- Atom interferometry

02- Atomic clocks

15- Precision measurements and tests of fundamental physics

Topic A - Precision measurements

19- Spectroscopy

Topic B - Ultracold gases

06- Bose gases

Topic B - Ultracold gases

09- Dipolar gases

10- Fermi gases

13- Optical lattices

Topic C - Quantum

16- Quantum information

17- Quantum optics and cavity QED

18- Quantum simulators with atoms and ions

Topic D - Traps & Interactions

03- Atomic interactions and collisions

07- Cold neutral and ionic molecules, cold chemistry

08- Cooling and trapping of atoms and ions

11- From two body to manybody systems

Topic E - Atomic physics and beyond

04- Atoms in external fields

05- Beyond atomic physics (bio, optomechanics, astro, etc.)

12- Intense fields and ultrafast phenomena

14- Other

Invited Talks

Quantum simulations with ultracold bosons and fermions

Wolfgang Ketterle[1]

Research Laboratory for Electronics, MIT-Harvard Center for Ultracold Atoms, and Department of Physics, Massachusetts Institute of Technology, Cambridge, USA
ketterle@mit.edu

I will summarize recent work at MIT on quantum simulations. A two-component systems of bosons in optical lattices can realize spin Hamiltonians. We present Bragg scattering of light as a detection method for magnetic phases, analogous to neutron scattering in condensed matter systems. A two-component Fermi gas with repulsive interactions, described by the so-called Stoner model, was predicted to undergo a phase transition to a ferromagnetic phase. We show that the phase transition is preempted by pair formation. Therefore, the Stoner model is an idealization not realized in Nature, since the paired state cannot be neglected.

Anderson localization of ultra-cold atoms

Alain Aspect

Laboratoire Charles Fabry, Institut d'Optique/CNRS/Université Paris-Sud, Palaiseau, France
Alain.aspect@institutoptique.fr

Anderson localization is a phenomenon first proposed in the context of condensed matter physics, but also expected to exist in wave physics. It has been realized in recent years that ultra-cold atoms offer remarkable possibilities to observe experimentally Anderson localization [1], After presenting my naïve understanding of that fascinating problem, I will present some experimental results [2], and argue that ultra-cold atoms in a disordered potential can be considered a quantum simulator that should allow experimentalists to answer open theoretical questions.

References

[1] A. Aspect and M. Inguscio, *Anderson localization of ultracold atoms*, Physics Today 62 (2009) 30, and references in.
[2] F. Jendrzejewski, A. Bernard, K. Muller, P. Cheinet, V. Josse, M. Piraud, L. Pezze, L. Sanchez-Palencia, A. Aspect, and P. Bouyer, *Three-dimensional localization of ultracold atoms in an optical disordered potential*, Nature Physics 8 (2012) 398, and references in.

Phase slips and weak links: superfluidity in rotating "circuits" of ultra-cold atoms

K. C. Wright, R. B. Blakestad, C. J. Lobb, W. D. Phillips, and G. K. Campbell*

Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, Maryland, 20899-8424, USA
**gretchen.campbell@nist.gov*

Persistent currents are a hallmark of both superfluidity and superconductivity. Just as a current in a superconducting circuit will flow forever, if a current is created in a superfluid condensate, the flow will not decay. We have created a long-lived persistent current in a toroidal-shaped Bose-Einstein Condensate, and studied the behavior of the current in the presence of both stationary and rotating weak links. A repulsive optical barrier across one side of the torus creates the tunable weak link in the condensate circuit and can be used to control the current around the loop. For a stationary barrier, we find that superflow stops abruptly at a barrier strength where the local flow velocity exceeds a critical velocity [1]. With arotating weak link, at low rotation rates, we have observed phase slips between well-defined persistent current states. For higher rotation rates, we observe a transition to a regime where vortices penetrate the bulk of the condensate. These results demonstrate an important step toward realizing an atomic SQUID analog.

Reference

[1] A. Ramanathan, K. C. Wright, S. R. Muniz, M. Zelan, W. T. Hill III, C. J. Lobb, K. Helmerson,W. D. Phillips, G. K. Campbell, *Superflow in a Toroidal Bose-Einstein Condensate: An Atom Circuit with a Tunable Weak Link*, Phys. Rev. Lett **106**, 130401 (2011).

Invited Talk Ultracold Fermi gases

Probing the contact locally in a trapped unitary Fermi gas

Deborah S. Jin*, Yoav Sagi, Tara Drake, and Rabin Paudel

JILA, NIST and University of Colorado, and Physics Department, University of Colorado, Boulder, Colorado, USA
** jin@jilau1.colorado.edu*

The inherent density inhomogeneity of a trapped gas can complicate interpretation of experiments and can wash out sharp features. This is especially important for a Fermi gas, where interaction effects as well as the local Fermi energy, or Fermi momentum, depend on the density. We report on experiments that use optical pumping with shaped light beams to spatially select the center part of a trapped gas for probing. This technique is compatible with momentum-resolved measurements, and for a weakly interacting Fermi gas of ^{40}K atoms, we present measurements of the momentum distribution that reveal for the first time a sharp Fermi surface. We then apply this technique to a strongly interacting Fermi gas at the Feshbach resonance, where we probe Tan's contact locally in the trapped gas. Unlike the trap-averaged case, predictions for the homogeneous contact differ substantially around the critical temperature for different many-body theories of the BCS-BEC crossover.

Strongly interacting Fermi gases: thermodynamics and topological phases

Martin W. Zwierlein

MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Strongly interacting gases of ultracold fermions have become an amazingly rich test-bed for many-body theories of fermionic matter. I will present high-precision measurements on the thermodynamics of a strongly interacting Fermi gas across the superfluid transition [1]. The onset of superfluidity is directly observed in the compressibility, the chemical potential, the entropy, and the heat capacity. Our measurements provide benchmarks for current many-body theories on strongly interacting fermions. Novel topological phases of matter are predicted for fermionic superfluids in the presence of spin-orbit coupling. We created and detected spin-orbit coupling in an atomic Fermi gas [2]. For energies within the spin-orbit gap, the system acts as a spin diode. To fully inhibit transport, we create a spin-orbit coupled lattice with spinful band structure. In the presence of s-wave interactions, such systems should display induced p-wave pairing, topological superfluidity, and Majorana edge states.

References

[1] Mark Ku, Ariel Sommer, Lawrence Cheuk, and Martin W. Zwierlein. „Revealing the Superfluid Lambda Transition in the Universal Thermodynamics of a Unitary Fermi Gas", Science **335**, 563 (2012).
[2] Lawrence W. Cheuk, Ariel T. Sommer, Zoran Hadzibabic, Tarik Yefsah, Waseem S. Bakr, Martin W. Zwierlein, „Spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas", arXiv:1205.3483 (2012).

Ultracold Fermi gases Invited Talk

Thermodynamics of quantum gases

B. Rem, A. Grier, I. Ferrier-Barbut, U. Eismann, A. Bergschneider, T. Langen, N. Navon, S. Nascimbène, F. Chevy, and C. Salomon*

Laboratoire Kastler Brossel, CNRS, UPMC, Département de Physique de l'École normale supérieure, 24 rue Lhomond, 75231, Paris, France
**salomon@lkb.ens.fr*

Ultracold dilute atomic gases can be considered as model systems to address some pending problem in Many-Body physics that occur in condensed matter systems, nuclear physics, and astrophysics. We have developed a general method to probe with high precision the thermodynamics of locally homogeneous ultracold Bose and Fermi gases [1,2,3]. For attractive spin 1/2 fermions with tunable interaction (^{6}Li), we will show that the gas thermodynamic properties can continuously change from those of weakly interacting Cooper pairs described by Bardeen-Cooper-Schrieffer theory to those of strongly bound molecules undergoing Bose-Einstein condensation. A detailed comparison with theories including recent Monte-Carlo calculations will be presented. Moving away from the unitary gas, the Lee-Huang-Yang and Lee-Yang beyond-mean-field corrections for low density bosonic and fermionic superfluids are quantitatively measured for the first time. Finally we will present a precision measurement of the three-body recombination rate of a unitary Bose gas as a function of temperature.

References

[1] S. Nascimbène, N. Navon, K. Jiang, F. Chevy, and C. Salomon, Nature **463**, 1057 (2010).
[2] N. Navon, S. Nascimbène, F. Chevy, and C. Salomon, Science **328**, 729 (2010).
[3] S. Nascimbène *et al.*, Phys. Rev. Lett. **106**, 215303 (2011).

The electric dipole moment of the electron

E. A. Hinds*, J. J. Hudson, D. M. Kara, I. J. Smallman,
J. Devlin, M. R. Tarbutt, and B. E. Sauer

Centre for Cold Matter, Imperial College London, Prince Consort Road, London SW7 2AZ, UK
**ed.hinds@imperial.ac.uk*

According to the standard model of elementary particle physics, the electric dipole moment (EDM) of the electron is $d_e \simeq 10^{-38}$ e.cm - currently far too small to observe. However, most extensions to the standard model predict much larger values, potentially accessible to measurement [1]. Hence, the search for the electron EDM is a search for physics beyond the standard model. In particular, the electron EDM is sensitive to new interactions that violate CP symmetry. It is considered that such interactions must be present in nature since the observed universe exhibits a strong excess of matter over antimatter [2]. I will survey the current status of ongoing experiments to measure the electron EDM, with particular emphasison the YbF experiment [3], which provides the most accurate measurement at present. I will also discuss prospects for further major improvements in sensitivity through the laser cooling of suitable molecules.

References

[1] E. D. Commins, *Electric dipole moments of leptons*, Adv. At., Mol., Opt. Phys., **40**, 1-56 (1999).
[2] A. D. Sakharov, *Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe*, JETP, **5**, 24 (1967), republished as Sov. Phys. Usp.**34**, 392 (1991).
[3] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, E. A. Hinds, *Improved measurement of the shape of the electron*, Nature, **473**, 493 (2011).

Physics with trapped antihydrogen

J. S. Hangst

Department of Physics and Astronomy, Aarhus University, and Spokesperson, the ALPHA collaboration at CERN
jeffrey.hangst@cern.ch

Antihydrogen, the bound state of an antiproton and a positron, can be used as a test-bed of fundamental symmetries. In particular, the CPT Theorem requires that hydrogen and antihydrogen have the same spectrum. The current experimental precision of measurements of hydrogen transition frequencies approaches one part in 10^{14}. Similarly precise antihydrogen spectroscopy would constitute a unique, model-independent test of CPT symmetry. Antihydrogen atoms have been produced in quantity at CERN since 2002, when the ATHENA collaboration demonstrated [1] how to mix cryogenic plasmas of antiprotons and positrons to produce low energy anti-atoms. In this colloquium I will discuss the newest development along the road to antihydrogen spectroscopy: magnetically trapped antihydrogen. In November of 2010 the ALPHA collaboration reported the first [2] trapping of antihydrogen atoms in a magnetic multipole trap. The atoms must be produced with an energy - in temperature units - of less than 0.5 K in order to be trapped. Subsequently, we have shown that trapped antihydrogen can be stored [3] for up to 1000 s, and we have performed the first resonant interaction experiments with anti-atoms [4]. I will discuss the many developments necessary to realise trapped antihydrogen, and I will take a look at the future of antihydrogen physics at CERN.

References

[1] Amoretti, M. et al., Nature **419**, 456 (2002).
[2] Andresen, G. B. et al., Trapped Antihydrogen, Nature, **468**, 673 (2010).
[3] Andresen, G. B. et al. Nature Physics **7**, 558 (2011).
[4] Amole, C. et al., Nature **483**, 439 (2012).

Astrophysical evidences for the variation of fundamental constants and proposals of laboratory tests

V. V. Flambaum

School of Physics, University of New South Wales, Sydney 2052, Australia
v.flambaum@unsw.edu.au

I present a review of recent results on a search for space-time variation of the fundamental constants. New results for the variation of the fine structure constant alpha, based on the quasar absorption spectra data, indicate the variation of alpha in space. The spatial variation can explain fine tuning of the fundamental constants which allows humans (and any life) to appear. We appeared in the area of the Universe where the values of the fundamental constants are consistent with our existence. There is an agreement between the results obtained using different telescopes and different redshifts. Also, now there are no contradictions between the results obtained by different groups. These astrophysical results may be used to predict the variation effects for atomic clocks. The effects (which appear due to Sun and Earth motions) are very small and require improvement of the clock accuracy by 1-2 orders of magnitude. The improvement of the clock sensitivity may be achieved using ^{229}Th nuclear clocks where expected accuracy of the frequency measurement is 10^{-19} and the effect of the variation is enhanced by 4-5 orders of magnitude. A comparable accuracy of the frequency measurements may be also achieved in highly charged ions where the effects of the variation are enhanced by an order of magnitude. We found a number of allowed E1 and narrow higher multipolarity clock transitions in such ions. The frequencies are in the laser range due to the configuration crossing phenomenon. There are also enhanced effects in some atomic and molecular transitions. Atomic clocks can also be used to measure possible dependence of the fundamental constants on environment (e.g. density of matter) and gravity.

Precision metrology and many-body quantum physics

Jun Ye

JILA, NIST and University of Colorado, 440 UCB, Boulder, CO 80309, USA

I will present our latest advances in a Sr optical atomic clock where we have achieved measurement precision of 1×10^{-17} fractional frequency at a measurement time of 1000 s. This unprecedented spectroscopic capability has allowed us to characterize density-related systematic uncertainty below 1×10^{-18}. It has also enabled us to explore many-body quantum dynamics where seemingly weak atomic interactions give rise to correlated states.

A gravitational wave observatory operating beyond the quantum shot-noise limit: squeezed light in application

Roman Schnabel

Institut für Gravitationsphysik, Leibniz Universität Hannover, Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Hannover, Germany
roman.schnabel@aei.mpg.de

Current gravitational wave (GW) detectors are Michelson-type kilometre-scale laser interferometers measuring the distance changes between in vacuum suspended mirrors. The sensitivity of these detectors at frequencies above several hundred hertz is limited by the vacuum (zero-point) fluctuations of the electromagnetic field. A quantum technology - the injection of squeezed light [1] - offers a solution to this problem. This talk will review recent progress on the generation of squeezed light, and also the recent squeezed-light enhancement of GEO600 [2], which will be the GW observatory operated by the LIGO Scientific Collaboration in its search for GWs for the next 3-4 years. GEO600 now operates with its best ever sensitivity, which proves the usefulness of quantum entanglement and the qualification of squeezed light as a key technology for future GW astronomy.

References
[1] C. M. Caves, "Quantum-mechanical noise in an interferometer", Phys. Rev. D **23**, pp. 1693-1708 (1981).
[2] The LIGO Scientific Collaboration, "A gravitational wave observatory operating beyond the quantum shot-noise limit", Nature Physics **7,** pp. 962-965 (2011).

Building a metrological toolbox for harnessing atoms and molecules

Paolo De Natale[1,2]

1. CNR - Istituto Nazionale di Ottica, Largo E. Fermi, 6 I-50125 Firenze, Italy
2. LENS (European Laboratory for Non-linear Spectroscopy), Via Carrara 1, 50019 Sesto Fiorentino (FI), Italy
paolo.denatale@ino.it

Interrogation and manipulation of atomic and molecular transitions for challenging experiments put increasingly demanding constraints on sources, detectors and techniques. Key parameters like continuous coverage of extreme spectral regions, tight control of phase and frequency fluctuations, implementation of ultra-low noise techniques have the power to disclose new avenues for frontier research and, subsequently, change our way and quality of life. I will give an overview of recent results aiming at a study of new infrared sources and spectroscopic techniques, obtained at INO-CNR and LENS [1]. Applications to molecules [2] and atoms [3] will be shown.

References
[1] M. Vitiello et al., "Quantum-limited frequency fluctuations in a Terahertz laser", Nature Photonics, in press (2012).
[2] I. Galli et al., "Molecular Gas Sensing Below Parts Per Trillion: Radiocarbon-Dioxide Optical Detection", Phys. Rev. Lett. **107**, 270802 (2011).
[3] P. Cancio Pastor et al., "Frequency Metrology of Helium around 1083 nm and Determination of the Nuclear Charge Radius", Phys. Rev. Lett. **108**, 143001 (2012).

Quantum networks of atoms

Christopher Monroe

Joint Quantum Institute and University of Maryland, College Park, MD, USA
monroe@umd.edu

Trapped atomic ions are standards for quantum information processing, with each atom storing a quantum bit (qubit) of information in appropriate internal electronic states. The Coulomb interaction mediates entangling quantum gate operations through the collective motion of the ion crystal, which can be driven through state-dependent optical dipole forces. Scaling to larger numbers of trapped ion qubits can be accomplished by either physically shuttling the individual atoms through advanced microfabricated ion trap structures or alternatively by mapping atomic qubits onto photons for the entanglement over remote distances. Such a quantum network will impact quantum information processing, quantum simulation of models from condensed matter, quantum communication, and the quest for building ever larger entangled quantum states and perhaps entangling atoms with other physical platforms such as quantum dots or macroscopic mechanical systems. Work on these fronts will be reported, including quantum simulations of magnetism with N=16 atomic qubits and the uses of entanglement of matter over macroscopic distances.

Towards large-scale entanglement in a string of trapped ions

B. P. Lanyon[1,2,*], C. Hempel[1,2], D. Nigg[2], M. Müller[1,3], R. Gerritsma[1,2], F. Zähringer[1,2], P. Schindler[2], J. T. Barreiro[2], M. Rambach[1,2], G. Kirchmair[1,2], M. Hennrich[2], P. Zoller[1,3], R. Blatt[1,2], and C. F. Roos[1,2]

1. Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, A-6020 Innsbruck, Austria
2. Institut für Experimentalphysik, University of Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria,
3. Institut für Theoretische Physik, University of Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria
**ben.lanyon@uibk.ac.at*

Recently, small strings of ultra-cold trapped ions have been used to precisely simulate and calculate properties of other quantum systems. I will briefly review our recent work in this direction [1]. Here we showed how ion strings can be manipulated to simulate any other quantum system, using a stroboscopic combination of quantum logic gates. A key challenge now is to scale up simulation size and complexity, to a level where new insights into many-body quantum phenomena are possible. I will discuss our plans to perform simulations using long ion strings and generate large-amounts of non-classical correlations which cannot be represented classically.

Reference

[1] B. P. Lanyon *et al*, Universal digital quantum simulation. *Science*, **334**, pp. 57–61, (2011).

Quantum dynamics of a mobile single-spin impurity in an optical lattice

Stefan Kuhr[1,2]

1. University of Strathclyde, Department of Physics, Glasgow G4 0NG, UK
2. Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str 1, 85748 Garching, Germany
stefan.kuhr@strath.ac.uk

The Heisenberg model is fundamental to quantum magnetism, as it describes properties of many materials such as transition metal oxides and cuprate superconductors. Mobile spin impurities are unique probes of its physics but are usually difficult to track in a space-time resolved way. Ultracold atoms in optical lattices offer an ideal testbed for these phenomena, in particular the novel techniques for single-atom imaging [1] and single-spin addressing [2] with a high-resolution optical microscope. Using this technique we have prepared a single spin impurity in a one-dimensional Mott insulator and have directly observed its coherent quantum dynamics. We measured its propagation velocity as the system undergoes the transition from a Mott insulator to a superfluid and found excellent agreement with analytical and numerical predictions. We also used the high-resolution imaging technique for in-situ detection of individual Rydberg excitations in a 2D atomic Mott insulator, and we could directly observe Rydberg blockade and crystalline states of the excitations.

References

[1] W. Bakr et al., A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice, Nature , 74 (2009); J. Sherson et al., Single-atom-resolved fluorescence imaging of an atomic Mott insulator, Nature **467**, 68 (2010).
[2] C. Weitenberg et al., Single-spin addressing in an atomic Mott insulator, Nature **471**, 319 (2011).

Progress towards measuring the electron EDM with thorium monoxide

Cheong Chan[1], David DeMille[1], John M. Doyle[2], Gerald Gabrielse[2], Paul Hess[2], Nicholas R. Hutzler[2,*], Emil Kirilov[2], Brendon O'Leary[2], Elizabeth Petrik[2], and Ben Spaun[2]

1. Yale University Physics Department, New Haven, CT, USA
2. Harvard University Physics Department, Cambridge, MA, USA
** hutzler@physics.harvard.edu*

Measurement of a non-zero electric dipole moment (EDM) of the electron within a few orders of magnitude of the current best limit [1] of $|d_e|<1.05*10^{-27}$ e*cm would be an indication of CP violation beyond the Standard Model. The ACME Collaboration is searching for an electron EDM by performing a precision measurement of electron spin precession signals from the metastable H $^3\Delta_1$ state of thorium monoxide (ThO), using a cold and slow beam. We discuss the current status of the experiment. Based on a data set acquired from 14 hours of running time over a period of two days, we have achieved a one-sigma statistical uncertainty of $\delta d_e=1*10^{-28}$ e*cm/$\sqrt{T}$, where T is the running time in days.

Reference

[1] J. J. Hudson et al., "Improved measurement of the shape of the electron." Nature 473, 493 (2011).

Accurate determination of the Boltzmann constant by Doppler spectroscopy: towards a new definition of the Kelvin

B. Darquié*, S. Mejri, P. L. T. Sow, C. Lemarchand, C. Bordé, C. Chardonnet, and C. Daussy

Laboratoire de Physique des Lasers, UMR7538 CNRS/Université Paris 13, Villetaneuse, France
**benoit.darquie@univ-paris13.fr*

Accurate molecular spectroscopy in the mid-infrared region allows precision measurements of fundamental constants. For instance, measuring the linewidth of an isolated Doppler-broadened absorption line of ammonia around 10 µm enables a determination of the Boltzmann constant k_B [1]. We report on our latest measurements. By fitting this lineshape to several models which include Dicke narrowing and speed-dependent collisional effects, we find that a determination of k_B with an uncertainty of a few ppm is reachable [2]. This is comparable to the current world limit obtained using acoustic methods and would make a significant contribution to any new value of k_B determined by the CODATA. Furthermore, having multiple independent measurements at these accuracies opens the possibility of defining the Kelvin by fixing k_B, an exciting prospect considering the upcoming redefinition of the International System of Units (SI).

References

[1] C. Lemarchand et al., Progress towards an accurate determination of the Boltzmann constant by Doppler spectroscopy, New J. Phys. **13**, 073028 (2011).
[2] M. Triki et al., Evidence for speed-dependent effects in NH_3 self-broadened spectra: towards a new determination of the Boltzmann constant, arXiv:1201.4087v1 (2012).

Frequency metrology in quantum degenerate helium

Rob van Rooij[1], Joe Borbely[1], Juliette Simonet[2], Maarten Hoogerland[2], Kjeld Eikema[1], Roel Rozendaal[1], and Wim Vassen[1,*]

1. LaserLaB VU University, Amsterdam, the Netherlands
ENS, LKB, Paris, France
2. Department of Physics, University of Auckland, New Zealand
** w.vassen@vu.nl*

We have measured the absolute frequency of the 1557-nm doubly forbidden transition between the two metastable states of helium, $2\ ^3S_1$ (lifetime 8000 s) and $2\ ^1S_0$ (lifetime 20 ms), with 1 kHz precision [1].With an Einstein coefficient of 10^{-7} s^{-1} this is one of weakest optical transitions ever measured. The measurement was performed in a Bose-Einstein condensate of $^4He^*$ as well as in a Degenerate Fermi Gas of $^3He^*$, trapped in a crossed dipole trap. From the isotope shift we deduced the nuclear charge radius difference between the α-particle and the helion. Our value differs by 4σ with a very recent result obtained on the $2\ ^3S \rightarrow 2\ ^3P$ transition [2].

References

[1] R. van Rooij, J. S. Borbely, J. Simonet, M. D. Hoogerland, K. S. E. Eikema, R. A. Roozendaal, W. Vassen, “Frequency metrology in quantum degenerate helium: Direct measurement of the $2\ ^3S_1 \rightarrow 2\ ^1S_0$ transition”, Science **333**, 196 (2011).
[2] P. Cancio Pastor, L. Consolino, G. Giusfredi, P. De Natale, M. Inguscio, V. A. Yerokhin, K. Pachucki, “Frequency metrology of helium around 1083 nm and determination of the nuclear charge radius”, Phys. Rev. Lett. **108**, 143001 (2012).

Cavity Quantum Electrodynamics with real and artificial atoms

Serge Haroche

Collège de France and Laboratoire Kastler Brossel, CNRS/Université Paris-VI, France
haroche@lkb.ens.fr

Cavity Quantum Electrodynamics (CQED) deals with the strong coupling of atoms with quantized radiation field modes stored in high-Q cavities. In the microwave domain, it consists in coupling large electric-dipole-carrying Rydberg atoms to a very high Q superconducting cavity. With this system fundamental tests of quantum physics have been realized and basic quantum information procedures demonstrated. Microwave CQED has been recently extended into a new domain of mesoscopic physics called "Circuit-QED",where artificial atoms made of superconducting Josephson junctions interact with high-Q coaxial radiofrequency resonators. These systems, based on well-developed solid state technology, are very promising for quantum information science. Atomic CQED and"Circuit-QED" bear strong similarities and also present some marked differences which will be illustrated by the description of recent experiments belonging to both fields.

Quantum network with individual atoms and photons

Gerhard Rempe

Max-Planck Institute of Quantum Optics, Hans-Kopfermann-Str.1, D-85748 Garching, Germany
gerhard.rempe@mpq.mpg.de

Quantum physics allows a new approach to information processing. A grand challenge is the realization of a quantum network for long-distance quantum communication and large-scale quantum simulation [1]. The talk will highlight a first implementation of an elementary quantum network with two fiber-linked high-finesse optical resonators, each containing a single quasi-permanently trapped atom as a stationary quantum node [2]. Reversible quantum state transfer between the two atoms and entanglement of the two atoms are achieved by the controlled exchange of a time-symmetric single photon. This approach to quantum networking is efficient and offers a clear perspective for scalability. It allows for arbitrary topologies and features controlled connectivity as well as, in principle, infinite-range interactions. Our system constitutes the largest man-made material quantum system to date and is an ideal test bed for fundamental investigations, e.g. quantum nonlocality.

References

[1] J. I. Cirac *et al*., "Quantum state transfer and entanglement distribution among distant nodes in a quantum network", Phys. Rev. Lett. **78**, pp. 3221-3224 (1997).
[2] S. Ritter *et al*., "An Elementary Quantum Network of Single Atoms in Optical Cavities", Nature **484**, pp. 195-200 (2012).

Cavity QED and quantum optics with a single quantum dot in a photonic crystal cavity or a photonic molecule

Jelena Vuckovic[1,*], Arka Majumdar[1], Michal Bajcsy[1], Armand Rundquist[1], Konstantinos Lagoudakis[1], Dirk Englund[1,2], and Andrei Faraon[1,3]

1. Ginzton Laboratory and Department of Electrical Engineering, Stanford University, Stanford, CA, USA
2. Columbia University, New York, NY, USA
3. HP Labs, Palo Alto, CA, USA
** jela@stanford.edu*

Quantum dots (QDs) in photonic crystal (PC) cavities are interesting both as a test-bed for fundamental studies of quantum optics and cavity QED, as well as a platform for classical and quantum information processing. Namely, as a result of the strong field localization inside of sub-cubic wavelength volumes in such cavities and a large QD dipole moment, they enable very large emitter-field interaction strengths (vacuum Rabi frequencies in the range of 10-25GHz). We have employed a platform consisting of a single self-assembled InAs QD in a GaAs PC cavity to study quantum optics and cavity QED. We have also probed ultrafast dynamics and strong optical nonlinearity that occur in the strong coupling regime, and employed them to achieve controlled amplitude and phase shifts between two optical beams at the single photon level and at the 25GHz speed. We have also probed the ladder of dressed states of the strongly coupled QD-cavity system and studied the regimes of photon blockade and photon induced tunneling, as well as nonclassical light generation enabled by this ladder. Finally, we have demonstrated strong coupling between a single quantum dot and a photonic molecule consisting of two coupled PC cavities, which is useful for nonclassical light generation and potentially even quantum simulation.

Quantum storage and manipulation using gradient echo memory

M. Hosseini, B. M. Sparkes, G. T. Campbell, D. Higginbottom, O. Pinel, M. Rancic, B. C. Buchler, and P. K. Lam

Centre for Quantum Computation and Communication Technology, Department of Quantum Science
The Australian National University, Canberra, ACT0200, Australia

We present a coherent optical memory scheme that is able to efficiently store, process, and recall optical information on demand. Our scheme is based on the controlled reversible inhomogeneous broadening (CRIB) mechanism [1], but with some additional control parameters. Using a Raman transition and a gradient field to introduce a linear atomic detuning in the propagation direction, the gradient echo memory (GEM) has been shown to be efficient, versatile and noiseless[2]. We use the theory of *k*-space polaritons to describe the dynamics of multiple pulse storage in GEM. We show experimental results of the GEM system implemented using warm Rb vapour cell. Storage and retrieval of a single optical pulse with efficiency as high as 87% has been observed [2]. We also show multiple pulse storage, spectral manipulation, image storage and a quantum characterization of the noise properties of GEM.

References

[1] B. Kraus et al., Quantum memory for nonstationary light fields based on controlled reversible inhomogeneous broadening, Phys. Rev. A **73**, 020302(R) (2006).
[2] G. Hétet et al. Electro-optic quantum memory for light using two-level atoms, Phys. Rev. Lett. **100**, 023601 (2008); M. Hosseini et al. Coherent optical pulse sequencer for quantum applications, Nature **461**, 241 (2009); M. Hedges et al. Efficient quantum memory for light Nature **465** 1052 (2010); M. Hosseini et al High efficiency coherent optical memory with warm rubidium vapour Nature Commun. **7** 794 (2011).

Tunable gauge potential for spinless particles in driven lattices

J. Simonet[1,*], J. Struck[1], M. Weinberg[1], C. Ölschläger[1],P. Hauke[2], A. Eckardt[3], P. Windpassinger[1], M. Lewenstein[2], and K. Sengstock[1]

1. Institut für Laserphysik, Universität Hamburg, Hamburg, Germany
2. Institut de Ciències Fotòniques, Barcelona, Spain
3. Max-Planck-Institut für Physik komplexer Systeme, Dresden, Germany
**jsimonet@physnet.uni-hamburg.de*

We present a universal method to create a tunable, artificial vector gauge potential for neutral particles trapped in an optical lattice. A suitable periodic shaking of the lattice allows to engineer a Peierls phase for the hopping parameters. This schemethus allows one to address the atomic internal degrees of freedom independently. We experimentally demonstrate the realization of such artificial potentials in a 1D lattice, which generate ground state superfuids at arbitrary non-zero quasi-momentum [1].

This scheme offers fascinating possibilities to emulate synthetic magnetic fields in 2D lattices. In a triangular lattice, continuously tunable staggered fluxes are realized. Spontaneous symmetry-breaking has recently been observed for a π-flux [2]. With the presented scheme, we are now able to study the influence of a small symmetry-breaking perturbation.

References

[1] J. Struck et al., arXiv:1203.0049 (2012).
[2] J. Struck et al., Science **333**, 996 (2011).

Hot topic Quantum

A superradiant laser with <1 intracavity photon

James K. Thompson*, Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Dominic Meiser, and Murray J. Holland

JILA, NIST, and Dept. of Physics, University of Colorado, Boulder, Colorado
**jkt@jila.colorado.edu*

We will describe a recently demonstrated cold-atom Raman laser that operates deep into the superradiant or bad-cavity regime [1]. The system operates with <1 intracavity photon and with an effective excited state decay linewidth <1 Hz. This model system demonstrates key physics for future active optical clocks (similar to masers) that may achieve frequency linewidths approaching 1 mHz due to 3 to 5 orders of magnitude reduced sensitivity to thermal mirror noise. The measured linewidth of our model system demonstrates that the superradiant laser's frequency linewidth may be below the single particle dephasing and natural linewidths, greatly relaxing experimental requirements on atomic coherence. The light field's phase provides a continuous non-destructive measurement of the collective atomic phase with a precision that in-principle can be near the standard quantum limit. The possibilities for future hybrid active/passive atomic clocks will be discussed.

Reference

[1] Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Dominic Meiser, Murray J. Holland, and James K. Thompson, "A steady-state superradiant laser with less than one intracavity photon", Nature **484**, pp. 78-81 (2012).

Interaction-based spin measurements in a cold atomic ensemble

Mario Napolitano[1], Marco Koschorreck[1], Brice Dubost[1], Naeimeh Behbood[1], Robert Sewell[1], and Morgan W. Mitchell[1,2,*]

1. ICFO - Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
2. ICREA - Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain
**morgan.mitchell@icfo.es*

We demonstrate quantum-limited interaction-based measurement [1], in which interactions among probe particles are responsible for the observed signal [2]. This approach differs from squeezing-based quantum metrology in that 1) it does not require entanglement and 2) its sensitivity can improve faster than the usual Heisenberg limit $\delta\phi \propto N^{-1}$. We produce interactions between the $N = 10^5 - 10^8$ photons in a 50 ns optical pulse by passing them through acold atomic ensemble in an optical dipole trap. The photons experience non-linear Faraday rotation in proportion to the collective spin F of the ensemble, providing a sensitivity $\delta F \propto N^{-3/2}$, observed over two orders of magnitude in N.

References
[1] M. Napolitano, M. Koschorreck, B. Dubost, N. Behbood, R. J. Sewell, and M. W. Mitchell, Interaction-based quantum metrology showing scaling beyond the Heisenberg limit, Nature **471**, 486–489 (2011).
[2] S. Boixo, A. Datta, M. J. Davis, S. T. Flammia, A. Shaji, and C. M. Caves, Quantum Metrology: Dynamics versus Entanglement, Phys. Rev. Lett. **101**, 040403 (2008).

Atoms and molecules… Invited Talk

Exploring and controlling quantum gases under extreme conditions

Immanuel Bloch[1,2]

1. Max-Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching b. München, Germany
2. Ludwig-Maximilians-Universität, Fakultät für Physik, Schellingstr. 4, 80799 München, Germany
immanuel.bloch@mpq.mpg.de

Ultracold quantum gases in optical lattices offer a highly controlled setting to investigate quantum matter under extreme conditions. Close to the quantum critical point in the transition from a superfluid to a Mott insulator, the long wavelength behavior of a superfluid can be described by a Lorentz invariant field theory that leads to a Higg's type particle in the excitation spectrum. We show the existence of such a Higgs mode in a two-dimensional superfluid. Characteristic features of the mode will be discussed in the talk. In addition, I will present results on the realization of strong artificial magnetic fields using laser assisted hopping in optical lattices. The extreme field strengths reached in our experiment correspond to several thousands of Tesla that would have to applied to real material system to realize equivalent magnetic fluxes. Finally, I will present recent results on the first realization of thermodynamically stable negative temperature states for matter and discuss prospects to reach Bose-Einstein condensation at negative temperatures.

Altered interactions in artificial gauge fields

R. A. Williams[1], L. J. LeBlanc[1], K. Jiménez-García[1,2], M. C. Beeler[1], A. R. Perry[1], W. D. Phillips[1], and I. B. Spielman[1,*]

1. Joint Quantum Institute, National Institute of Standards and Technology, and and University of Maryland, Gaithersburg, Maryland, 20899, USA
2. Departamento de Física, Centro de Investigación y Estudios Avanzados del Instituto Politécnico Nacional, México D.F., 07360, México
**ian.spielman@nist.gov*

Interactions between particles can be strongly altered by their environment. Here we demonstrate a technique for modifying interactions between ultracold atoms by dressing the bare atomic states with light, creating a screened interaction of vastly increased range that scatters states of higher angular momentum at collision energies where only *s*-wave scattering would normally be expected. We optically dressed two neutral atomic Bose-Einstein condensates with a pair of lasers – linking together threedifferent internal atomic states – and then collided these condensates with the equal, and opposite, momenta of just two optical photons per atom. In agreement with our theoretical model, the usual ***s***-wave distribution of scattered atomswas altered by the appearance of ***d***- and ***g***-wave contributions [1].

Reference

[1] R. A. Williams *et al*, *Beyond s-wave interactions for ultracold atoms*, Science **355**, pp. 314-317 (2012).

Transport of impurities in optical lattices

Dieter Jaksch[1,2,3,*], Tomi Johnson[1], Martin Bruderer[4], and Stephen Clark[2,1,3]

1. Clarendon Laboratory, University of Oxford, OX1 3PU Oxford, UK
2. Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543
3. Keble College, University of Oxford, Parks Road, Oxford OX1 3PG, UK
4. Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany
**Dieter.Jaksch@physics.ox.ac.uk*

The transport and coherence properties of impurity atoms are strongly influenced by their interactions with a background optical lattice gas [1]. We discuss two resulting possible applications of impurity atoms: (i) studies of quantum transport through lattices with an engineered and well controlled phononic bath, for example allowing the realization of non-markovian impurity-bath couplings; and (ii) measurement of optical lattice gas properties through impurity measurements, for instance to distinguish different phases of the background gas. Finally, we investigate the influence of dephasing and dissipation on transport properties in more general spin-chain setups. It is shown how dephasing and incoherent couplings between spin chains can improve spin transport. We discuss how such setups could be simulated with optical lattices and hence provide important insights, for instance into exciton transport through conjugate polymers.

Reference

[1] T. H. Johnson, S. R. Clark, M. Bruderer and D. Jaksch, "Impurity transport through a strongly interacting bosonic quantum gas", Phys. Rev. A **84**, 023617 (2011).

Three universal trimers in ultracold atoms

Masahito Ueda

Department of Physics,University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan
ueda@phys.s.u-tokyo.ac.jp

We discuss three distinct types of universal trimers: Efimov, Kartavtsev-Malykh, and crossover trimers. In mass-imbalaced systems, they appear in various parameter regimes and are universal in that they do not depend on short-range details other than the scattering length and the three-body parameter, whereas they are distinguished from each other in their scaling property. The Efimov, Kartavtsev-Malykh, and crossover trimers respectively feature discrete, continuous, and no scale invariance. On the other hand, in systems of identical atoms, there has been mounting evidence that the three-body parameter is nearly constant in log scale not only across different universal regimes of one atomic species but also across different atomic species. We report the result of our numerical calculations based on a realistic Helium potential in agreement with experiemental results on Li, Rb, and Cs.

Tunable, deterministic few-fermion quantum systems

Gerhard Zürn[1,2], Thomas Lompe[1,2,3], Andre Wenz[1,2], Martin Ries[1,2], Vincent Klinkhamer[1,2], Andrea Bergschneider[1,2], Simon Murmann[1,2], and Selim Jochim[1,2,3,*]

1. Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Germany
2. Max-Planck-Institut für Kernphysik, Heidelberg, Germany
3. ExtreMe Matter Institute EMMI, GSI, Darmstadt, Germany
**jochim@uni-heidelberg.de*

Few-particle Fermi systems are the basic building blocks of all matter which have been studied extensively in atomic, nuclear and condensed matter physics. In our experiments, we have realized few-fermion systems consisting of 1-10 atoms in a tightly confining optical trap in which the interaction and all quantum mechanical degrees of freedom can be controlled. These deterministic ensembles are ideally suited for the quantum simulation of few-body systems.

To establish an experimental toolbox we first studied the two-particle system. By comparing a noninteracting spin polarized system with an interacting system containing two different spin states we could demonstrate fermionization of the two distinguishable particles for diverging repulsive coupling strength by showing that the square modulus of the wave function of the two systems is the same in our quasi 1-D configuration.

We have extended our study to up to six particles with both attractive and repulsive interactions. In the first case we observe a strong odd-even effect in the interaction energy and correlated pair tunneling out of a tilted trap. For strong repulsive interactions we observe ferromagnetic correlations, when the repulsion between distinguishable particles becomes stronger than the Fermi energy.

New physics with dipolar gases

Gora Shlyapnikov

Laboratoire de Physique Théorique et Modèles Statisatiques, CNRS/Université Paris-Sud, Bât. 100, 91405 Orsay, France
Van der Waals-Zeeman Institute, University of Amaterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

I will give an overview of the studies of dipolar quantum gases, focusing on their stability. After that the central issue will be novel quantum phases, such as the topological superfluid phase in two dimensions and interlayer superfluids in bilayer systems. The core of the discussion will be supersolid states for bosonic dipoles, in particular non-reactive polar molecules, in two dimensions. It will be emphasized how three-body interactions support the emergence of stable supersolid states.

Hot topic Ultracold gases

Quantum degenerate Bose and Fermi dipolar gases of dysprosium realized

Benjamin L. Lev, Mingwu Lu, and Nathaniel Q. Burdick

Departments of Applied Physics and Physics, Stanford University, Stanford, CA 94305, USA

Advances in the quantum manipulation of ultracold atomic gases are opening a new frontier in the quest to better understand strongly correlated matter. By exploiting the long-range and anisotropic character of the dipole-dipole interaction, we hope to create novel forms of soft quantum matter, phases intermediate between canonical states of order and disorder. Our group recently created Bose and Fermi quantum degenerate gases of the most magnetic element, dysprosium, which should allow investigations ofquantum liquid crystals. We present details of recent experiments that created the first degenerate dipolar Fermi gas [1] as well as the first strongly dipolar BEC in low field [2]. BECs of Dy will form the key ingredient in novel scanning probes using atom chips. We are developing a Dy cryogenic atom chip microscope that will possess unsurpassed sensitivity and resolution for the imaging of condensed matter materials exhibiting topologically protected transport [3] and magnetism.

References

[1] Lu, M. and Burdick, N. Q. and Lev, B. L, *Quantum Degenerate Dipolar Fermi Gas*, to appear in Phys. Rev. Lett.; arXiv:1202:4444 (2012).
[2] Lu, M. and Burdick, N. Q. and Youn, S.-H. and Lev, B. L, *Strongly Dipolar Bose-Einstein Condensate of Dysprosium*, Phys. Rev. Lett. **107**, 190401 (2011).
[3] Dellabetta, B. and Hughes, T. and Gilbert, M. and Lev, B. L, *Imaging topologically protected transport with quantum degenerate gases*, arXiv:1202:0060 (2012).

Bose-Einstein condensation of erbium

F. Ferlaino

Institut für Experimentalphysik and Zentrum für Quantenphysik,
Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria

We report on the production of the first Bose-Einstein condensate of erbium [1]. Erbium is a very special multi-valence-electron atom, belonging to the lanthanide series. It possesses a strongly magnetic dipolar character, a rich energy level diagram, and various isotopes, among which one has fermionic nature. Despite the complex atomic properties of such unconventional species, we find a surprisingly simple and efficient approach to reach quantum degeneracy by means of laser cooling on a narrow-line transition and standard evaporative cooling techniques. We observe favorable scattering properties of ^{168}Er, resulting in a remarkably high evaporation efficiency and in a large number of Feshbach resonances at very low magnetic field values($\approx$ 1 G). All these desirable properties make Er a dream system for ultracold quantum gas experiments.

Reference

[1] K. Aikawa, A. Frisch, M. Mark, S. Baier, A. Rietzler, R. Grimm, and F. Ferlaino, *Bose-Einstein Condensation of Erbium*, Phys. Rev. Lett. **108**, 210401 (2012).

Spin and density response of strongly interacting Fermi gases

Sascha Hoinka[1], Marcus Lingham[1], Kristian Fenech[1], and Chris J. Vale[1,*]

1. Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology,
Melbourne 3122, Australia
**cvale@swin.edu.au*

Ultracold Fermi gases near Feshbach resonances provide a unique strongly correlated many-body system that can be controlled and probed with high precision. These systems, characterised by short-range interactions and large scattering lengths, are challenging to describe theoretically and various approximate methods have been employed to make calculations tractable. Reliable experimental benchmarks are therefore a key requirement and progress is now demanding accuracies at the level of one percent. Here, we report on our precision experimental measurements of the density and spin dynamic and static structure factors of strongly interacting Fermi gases [1]. We use these to make the most precise determination of Tan's universal contact parameter [2] in a unitary Fermi gas and compare our results with different theoretical predictions. Progress towards obtaining the homogeneous contact from measurements on a trapped gas will also be presented.

References

[1] S. Hoinka, M. G. Lingham, M. Delehaye, and C. J. Vale, *Dynamic spin response of a strongly interacting Fermi gas*, arXiv:1203.4657 [cond-mat.quant-gas] (2012).

[2] S. Tan, *Energetics of a strongly correlated Fermi gas*, Ann. Phys. **323**, 2952 (2008).

Atomic physics with attosecond pulses

A. L'Huillier, D. Guénot, K. Klünder, J. M. Dahlström, D. Kroon, C. Arnold, P. Johnsson, J. Mauritsson, and M. Gisselbrecht

Department of Physics, Lund University, Sweden

When atoms are exposed to intense laser radiation, electrons in the ground state may tunnel ionize, acquire energy from the field, and recombine, leading to the generation of attosecond pulses with broad bandwidth. When this process is repeated many times, the emitted radiation takes the form of a frequency comb, with peaks at odd harmonics of the laser field. The first part of this presentation will describe some of the attosecond tools that are being developed ranging from single attosecond pulses to pulse trains and the techniques used to characterize them.

One of the most interesting properties of attosecond pulses is that thay can be used to measure both spectral phase and amplitude of an unknown wave function or wave packet by pump-probe interferometric methods, giving us access to the temporal dynamics of the process that led to this wave-packet. In this presentation, we will describe some of these applications, and in particular recent results concerning measurement of photoionization dynamics from different atomic subshells [1].

Reference

[1] K. Klünder *et al.*, "Probing single-photon ionization on the attosecond time scale" Phys. Rev. Lett. Phys. Rev. Lett. **106**, 143002 (2011).

Dynamics of electron wavepacket following tunnel ionization

Alexandra Landsman* and Ursula Keller

Institute of Quantum Electronics, ETH, Zurich, Switzerland
**landsmaa@phys.ethz.ch*

We give an overview of the dynamics of the electron wavepacket after strong field laser ionization. Strong field ionization can be viewed as a two-step process: first, the electron tunnels out of the atom, second, it is classically accelerated in the combined laser and Coulomb field. Of particular interest is the momenta distribution of the electron wavepacket just after it tunnels out of the atom. We reconstruct this distribution from the electron momenta measurements obtained at the detector and compare it to standard theoretical models. We also explore the creation of Rydberg states that occurs after tunnel ionization if the electron does not gain enough energy to escape the Coulomb force of the parent atom. The derived analytical formula clarifies the dependence of Rydberg electrons on ellipticity of laser light and shows excellent agreement with a prior experiment.

References

[1] A. S. Landsman, A. N. Pfeiffer, M. Smolarski, C. Cirelli, and U. Keller, "Rydberg states and momentum bifurcation in tunnel ionization with elliptically polarized light", arxiv: 111.6036.
[2] A. N. Pfeiffer, C. Cirelli, A. S. Landsman, M. Smolarski, D. Dimitrovski, and L. B. Madsen,, « Probing the longitudinal momentum spread of the electron wave packet at the tunnel exit.", arxiv: 1116033.

Ultrafast AMO physics at the LCLS x-ray FEL

Philip H. Bucksbaum

PULSE Institute, Department of Physics and Department of Applied Physics, Stanford University, and SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
contact.phb@slac.stanford.edu

The Linac Coherent Light Source (LCLS) located at the SLAC National Accelerator Laboratory at Stanford University is an x-ray laser with approximately one billion times higher brightness than any previous laboratory source of x-rays [1]. I will describe some of the first atomic, molecular, and optical physics experiments at LCLS, which have explored x-ray matter interactions in this new regime. These include nonlinear x-ray absorption, ultrafast experiments exploring the few-femtosecond time scale of Auger relaxation, and coherent x-ray-atom interactions. [2-4].

References

[1] P. Emma et al., Nature Photonics 4, 641 (2010).
[2] P. H. Bucksbaum, R. Coffee, N. Berrah, in Advances In Atomic, Molecular, and Optical Physics, E. Arimondo, P. R. Berman, C. C. Lin, Eds. (Academic Press, 2011), vol. 60, pp. 239-289.
[3] L. Young et al., Nature 466, 56 (2010).
[4] J. P. Cryan et al., Phys. Rev. Lett. 105, 083004 (2010).

Beyond atomic physics Invited Talk

Quantum interfaces: from ultra-cold atoms to solid-state systems

Mikhail Lukin

Physics Department, Harvard University, Cambridge, MA, 02138, USA
lukin@fas.harvard.edu

We will discuss several recent advances aimed at combining quantum control over ultra-cold atoms and solid-state atom-like systems with nanoscale optical and mechanical resonators. Novel applications of these techniques ranging from quantum nonlinear optics to nanoscale quantum sensing will be described.

Single molecule nanometry for biological physics

Hajin Kim[1] and Taekjip Ha[1,*]

1. Department of Physics, University of Illinois at Urbana-Champaign
**tjha@illinois.edu*

Precision measurement is a hallmark of physics but the small length scale (~ nanometer) of elementary biological components and the thermal fluctuations surrounding them challenge our ability to visualize the motion of biological molecules. Here, we highlight the recent developments in single molecule nanometry where the position of a single fluorescent molecule can be determined with nanometer precision [1] and the relative motion between two molecules can be determined with ~0.3 nmprecisionat ~1 millisecond time resolution [2], and how these new tools are providing fundamental insights on how motor proteins move on cellular highways [3]. We will also discuss how interactions between three and four fluorescent molecules can be used to measure three and six coordinates, respectively, allowing us to correlate movements of multiple components. Finally, we will discuss recent progress in combining angstrom precision optical tweezers with single molecule fluorescentdetection.

References
[1] A. Yildiz et al, Myosin V. Walks Hand over Hand: Single Fluorophore Imaging with 1.5 Nanometer Localization, Science **300** (5628), 2061-2065 (2003).
[2] S. Myong et al, Repetitive Shuttling of a Motor Protein on DNA, Nature **437**, 1321-1325 (2005).
[3] G. Lee et al, Elastic Coupling between RNA Degradation and Unwinding by an Exoribonuclease, Science (in press).

Quantum coherent coupling of light and mechanical motion

E. Verhagen[1], S. Deléglise[1], S. Weis[1], A. Schliesser[1], V. Sudhir[1], and T. J. Kippenberg[1,2]

1. EPFL, Lausanne, CH-1015, Switzerland
2. Max Planck Institute of Quantum Optics, 85748 Garching, Germany

Recent advances in nano- and micro-mechanical oscillators have for the first time allowed the observation of radiation pressure phenomena experimentally and constitute the emerging research field of *cavity optomechanics* [1]. Using on-chip micro-cavities that combine both optical and mechanical degrees of freedom in one and the same device [2], radiation pressure back-action of photons is shown to lead to effective cooling of the mechanical oscillator mode. In our research we prepare the oscillator with high ground state probability using cryogenic precooling to ca. 700 mK in conjunction with laser cooling, enabling cooling of micromechanical oscillator to only 1.7 quanta (37% ground state occupation). Moreover it is possible in this regime to observe quantum coherent coupling in which the mechanical and optical mode hybridize and the coupling rate exceeds the mechanical and optical de-coherence rate [3]. This accomplishment enables a range of quantum optical experiments, including state transfer from light to mechanics using the phenomenon of optomechanically induced transparency [4].

References
[1] T. J. Kippenberg, K. J. Vahala, Cavity Optomechanics: Backaction at the mesoscale. Science 321, 1172 (2008, 2008).
[2] A. Schliesser, et al. Radiation pressure cooling of a micromechanical oscillator using dynamical backaction. Physical Review Letters 97, 243905 (Dec 15, 2006).
[3] E. Verhagen, S. Deleglise, S. Weis, A. Schliesser, T. J. Kippenberg, Nature (2012).
[4] S. Weis *et al.*, Optomechanically Induced Transparency. *Science* **330**, 1520 (Dec, 2010).

Theory and experiments with quantum fluids of light

Iacopo Carusotto

INO-CNR BEC Center and Dipartimento di Fisica, Universita' di Trento, I-38123 Povo, Italy
carusott@science.unitn.it

A few years after the first observation of Bose-Einstein condensation, quantum gases of dressed photons in semiconductor microcavities (the so-called exciton-polaritons) are a powerful workbench for the study of many-body effects in a novel non-equilibrium context [1].

In this talk, I will first briefly review remarkable experiments investigating superfluid hydrodynamics effects in photon fluids hitting localized defects: depending on the flow speed, a wide range of behaviors have been observed, from superfluid flow, to the super-sonic Mach cone, to the nucleation of topological excitations such as solitons and vortices. I will then illustrate recent theoretical studies in the direction of generating strongly correlated photon gases, from Tonks-Girardeau gases of impenetrable photons in one-dimension [2], to quantum Hall liquids in the presence of artificial magnetic fields [3].

Advantages and disadvantages of the different material platforms in view of generating and detecting strongly correlated gases will be reviewed, in particular laterally patterned microcavity and micropillar devices in the optical range, and circuit-QED devices in the microwave domain.

References

[1] I. Carusotto and C. Ciuti, Rev. Mod. Phys., to appear (2012).
[2] I. Carusotto, D. Gerace, H. Tureci, S. De Liberato, C. Ciuti, A. Imamoglu,, Phys. Rev. Lett. , 033601 (2009).
[3] R. O. Umucalilar, I. Carusotto, preprint arXiv:1110.6524, to appear on Phys. Rev. Lett. (2012).

Attosecond control of collective charges in plasmas

Antonin Borot[1], Arnaud Malvache[1,*], Xiaowei Chen[1], Aurélie Jullien[1], Jean-Paul Geindre[2], Patrick Audebert[2], Gérard Mourou[3], Fabien Quéré[4], and Rodrigo Lopez-Martens[1]

1. Laboratoire d'Optique Appliquée, ENSTA-Paristech, Ecole Polytechnique, CNRS, Palaiseau
2. Laboratoire pour l'Utilisation des Lasers Intense, Ecole Polytechnique, CNRS, Palaiseau, France
3. Institut de la Lumière Extrême, ENSTA-Paristech, Ecole Polytechnique, CNRS, Palaiseau, France
4. Service des Photons, Atomes et Molécules, CEA, DSM/IRAMIS, Saclay, France
**arnaud.malvache@ensta-paristech.fr*

Today, light fields of controlled and measured waveform can be used to guide electron motion in atoms and molecules with attosecond precision. Here, we demonstrate attosecond control of collective electron motion in plasmas driven by extreme intensity (~10^{18} W.cm^{-2}) light fields. Controlled few-cycle near-infrared waves are tightly focused at the interface between vacuum and a solid-density plasma, where they launch and guide subcycle motion of electrons from the plasma with characteristic energies in the multi-kiloelectronvolt range — two orders of magnitude more than has been achieved so far in atoms and molecules. The basic spectroscopy of the coherent extreme ultraviolet radiation emerging from the light-plasma interaction allows us to probe this collective motion of charge with sub-200 attosecond resolution. This is an important step towards attosecond control of charge dynamics in laser-driven plasma experiments.

Reference

[1] A. Borot et al, "Attosecond control of collective electron motion in plasmas", Nat. Phys. **8**, pp. 416-421 (2012).

Hybrid atom-membrane optomechanics

M. Korppi[1], S. Camerer[2], A. Jöckel[1], D. Hunger[2], T. W. Hänsch[2], and P. Treutlein[1,*]

1. Department of Physics, University of Basel, Switzerland
2. Max-Planck-Institute of Quantum Optics and LMU Munich, Germany
**philipp.treutlein@unibas.ch*

In optomechanics, laser light is used for cooling and control of the vibrations of micromechanical oscillators, with many similarities to the cooling and trapping of atoms. It has been proposed that laser light could also be used to couple the motion of atoms in a trap to the vibrations of a mechanical oscillator [1]. In the resulting hybrid optomechanical system the atoms could be used to read out the oscillator, to engineer its dissipation, and ultimately to perform quantum information tasks.

We have realized a hybrid optomechanical system by coupling ultracold atoms to a micromechanical membrane [2]. The atoms are trapped in an optical lattice, formed by retro-reflection of a laser beam from the membrane surface, resulting in optomechanical coupling as proposed in [1]. We observe both the effect of the membrane vibrations onto the atoms as well as the backaction of the atomic motion onto the membrane. By coupling the membrane to laser-cooled atoms, we engineer the dissipation rate of the membrane. This mechanism can be used to sympathetically cool the membrane with the atoms.

References
[1] K. Hammerer, K. Stannigel, C. Genes, P. Zoller, P. Treutlein, S. Camerer, D. Hunger, and T. W. Hänsch, Phys. Rev. A **82**, 021803 (2010).
[2] S. Camerer, M. Korppi, A. Jöckel, D. Hunger, T. W. Hänsch, and P. Treutlein, Phys. Rev. Lett. **107**, 223001 (2011).

Feedback in a cavity QED system for control of quantum beats

A. D. Cimmarusti[1], B. D. Patterson[1], L. A. Orozco[1,*], P. Barberis-Blostein[2], and H. J. Carmichael[3]

1. Joint Quantum Institute, University of Maryland and NIST, College Park, Maryland, USA
2. IIMAS, Universidad Nacional Autonoma de México, México DF, México
3. Dept. of Physics, University of Auckland, Auckland, New Zealand
**lorozco@umd.edu*

Conditional measurements on the undriven mode of a two-mode cavity QED system prepare a coherent superposition of ground states that generate quantum beats [1]. The continuous drive of the system, through the phase interruptions from Rayleigh scattering, induces decoherence that manifests itself in a decrease of the amplitude and an increase of the frequency of the oscillations [2]. Our recent experiments implement a feedback mechanism to protect the quantum beat oscillation. We continuously drive the system until we detect a photon that heralds the presence of a coherent superposition. We then turn the drive off to let the superposition evolve in the dark, protecting it against decoherence. We later turn the drive back on to measure the amplitude, phase, and frequency of the beats. The amplitude can increase by more than fifty percent while the oscillations acquire a phase shift. Work supported by NSF, CONACYT, and the Marsden Fund of RSNZ.

References
[1] D. G. Norris, L. A. Orozco, P. Barberis-Blostein, and H. J. Carmichael, *Phys. Rev. Lett.* **105**, 123602 (2010).
[2] D. G. Norris, A. D. Cimmarusti, L. A. Orozco, P. Barberis-Blostein, and H. J. Carmichael, *Phys. Rev. A* **85**, 021804 (2012).

Monday Posters

A digital atom interferometer with single particle control

Andrea Alberti[1,*], Andreas Steffen[1], Wolfgang Alt[1], Noomen Belmechri[1], Sebastian Hild[1], Michał Karski[1], Artur Widera[2,1] and Dieter Meschede[1]

1. Institut für Angewandte Physik, Universität Bonn, Germany
2. Fachbereich Physik und Forschungszentrum OPTIMAS, Universität Kaiserslautern, Germany
**alberti@iap.uni-bonn.de*

Coherent control and delocalization of single trapped atoms constitute powerful new resources for quantum technologies. We will report on a single-atom interferometer that uses spin-dependent periodic potentials to coherently split and recombine particles with spatial separations of up to 24 lattice sites, equivalent to more than 10 μm. The interferometer geometry can be reprogrammed in a digital manner by freely assembling basic coherent operations at discrete time intervals; this allowed us to contrast different geometries and to develop a geometrical-analogue of the well-known spin-echo refocusing. We tested the interferometer by probing external potential gradients, achieving with single atoms 5×10^{-4} precision in units of gravitational acceleration g. Furthermore, a novel scheme for spin-dependent optical lattices is presently underway, with which we expect to reach splitting distances of 1 mm.

This coherent control of single-atom wave packets gives us a new way to investigate and exploit interaction effects between atoms; for instance, molecular bound states of two atoms are predicted to occur in quantum walk experiments as a result of matter-wave interference [1].

Reference

[1] A. Ahlbrecht, A. Alberti, D. Meschede, V. B. Scholz, A. H. Werner, R. F. Werner, Bound Molecules in an Interacting Quantum Walk, arXiv:1105.1051v1 (2011).

Atom interferometry Mo-002

Interferometry with chip based atom lasers

E. M. Rasel*, for the QUANTUS cooperation

QUEST, Institut fr Quantenoptik - Leibniz Universitt, Hannover, Germany
**rasel@iqo.uni-hannover.de*

We report on the implementation of a Bragg-type interferometer operated with a chip-based atom laser for Rubidium ^{87}Rb. With the chip based atom laser we can generate thermal ensemble as well as Bose-Einstein condensates (BEC) [1]. With the help of delta kick cooling [2], implemented via the atom chip, we can further slow down the expansion of thermal and condensed atoms. In addition, the chip allows to transfer atoms in the individual Zeeman states of the two hyperfine ground states, in particular into the non-magnetic state. With this toolbox we could extend the observation of a BEC of only 10000 atoms to macroscopic time scales approaching two seconds. Benefiting form the extended free fall in microgravity we could combine this with an asymmetric Mach-Zehnder type interferometer over hundreds of milliseconds to study the coherence and to analyze the delta kick cooling with the help of the observed interference fringes. This experiment can be considered as a double slit experiment in microgravity. NB: The QUANTUS cooperation comprises the group of C. Lämmerzahl (Univ. Bremen), A. Wicht (FBH), A. Peters (Humboldt Univ. Berlin), T. Hänsch/J. Reichel (MPQ/ENS), K. Sengstock (Univ. Hamburg), R. Walser (TU Darmstadt), and W. P. Schleich (Univ. Ulm).

References

[1] van Zoest *et al.*, *Bose-Einstein condensation in microgravity*, Science **328**, 1540 (2010).
[2] H. Amman and N. Christensen, *Delta Kick Cooling: A New Method for Cooling Atoms*, Phys. Rev. Lett., **78**, 2088 (1997).

Precision interferometry with Bose-Einstein condensates: toward a new measurement of the fine structure constant

Alan O. Jamison[1,*], Ben Plotkin-Swing[1], Anders Hansen[1], Alexander Khramov[1], William Dowd[1], J. Nathan Kutz[1,2], and Subhadeep Gupta[1]

1. Dept. of Physics, University of Washington, Seattle, USA
2. Dept. of Applied Mathematics, University of Washington, Seattle, USA
**jamisona@uw.edu*

We report progress, both theoretical and experimental, toward an atom interferometric measurement of $\hbar/M_{Yb}$, from which a value for the fine structure constant may be determined. By using a symmetric, three-arm contrast interferometer in free space many potential sources of systematic error cancel. For part per billion precision, such an interferometer requires two of the arms to be coherently accelerated. Experimental progress includes improved atom cooling efficiency, allowing production of large ($\sim 2.5 \times 10^5$ atom), nearly pure condensates of ^{174}Yb and faster cycle times for a low-momentum prototype interferometer. Theoretical progress includes new techniques for predicting mean-field effects for all interaction strengths, including the intermediate strength regime which is key to precision BEC interferometry [1]. These techniques are also valid for waveguide interferometers. A comparison of various coherent acceleration schemes will also be presented.

Reference

[1] A. O. Jamison, *et al.*, *Atomic Interactions in Precision Interferometry Using Bose-Einstein Condensates*, Phys. Rev. A, **84**, pp. 043643 (2011).

Quantum feedback control of atomic coherent states

Ralf Kohlhaas[1], Thomas Vanderbruggen[1], Andrea Bertoldi[1], Simon Bernon[1], Alain Aspect[1], Arnaud Landragin[2], and Philippe Bouyer[1,3,*]

1. Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique, RD 128, 91127 Palaiseau cedex, France
2. LNE-SYRTE, Observatoire de Paris, CNRS and UPMC, 61 avenue de l'Observatoire, F-75014 Paris, France
3. Laboratoire Photonique, Numérique et Nanosciences - LP2N, Université Bordeaux - IOGS - CNRS UMR 5298 - Bât. A30, 351 cours de la liberation, Talence, France
**philippe.bouyer@institutoptique.fr*

Quantum superposition states are under constant threat to decohere by the interaction with their environment. Active feedback control can protect quantum systems against decoherence, but faces the problem that the measurement process itself can change thequantum system. The adaptation of the measurement strategy to a given stabilization goal is therefore an essential step to implement quantum feedback control. Here, we present the protection of a collective internal state of an atomic ensemble against a simple decoherence model. A coherent spin state is prepared and exposed to a noise which randomly rotates the state on the Bloch sphere. We use weak nondestructive measurements with negligible projection of the atomic state which still give sufficient information to apply feedback. This method is used to increase the coherence lifetime of the initial superposition state by about one order of magnitude.

A novel cavity-based atom interferometer

Justin M. Brown[1,*], Brian Estey[1], and Holger Müller[1,2]

1. Department of Phyiscs, University of California Berkeley, Berkeley, CA 94720, USA
2. Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
**jmbrown@berkeley.edu*

The world's leading atom interferometers are housed in bulky atomic fountains. They employ a variety of techniques to increase the spatial separation between atomic clouds including high order Bragg diffraction. The largest momentum transfer in a single Bragg beamsplitter has been limited to 24 $\hbar k$ by laser power and beam quality [1]. We present an atom interferometer in a 40 cm optical cavity to enhance the available laser power, minimize wavefront distortions, and control other systematic effects symptomatic to atomic fountains. We expect to achieve spatial separations between atomic trajectories comparable to larger scale fountains within a more compact device. We report on progress in developing this new interferometer using cold Cs atoms and discuss its prospects for exploring large momentum transfer up to 100 $\hbar k$ in a single Bragg diffraction process. The compact design will enable the first demonstration of the gravitostatic Aharonov-Bohm effect [2].

References

[1] Holger Müller, Sheng-wey Chiow, Quan Long, Sven Herman, and Steven Chu. "Atom Interferometry with up to 24-Photon-Momentum-Transfer Beam Splitters". *Phys. Rev. Lett.*100(18), 180405, (2008).
[2] Michael A. Hohensee, Brian Estey, Paul Hamilton, Anton Zeilinger, and Holger Müller. "Force-free gravitational redshift: a gravitostatic Aharnonv-Bohm experiment". e-print: arXiv:1109.4887v2.

Coherent population transfer of cold ^{87}Rb atoms by counter-intuitive light pulses

Hoon Yu, Mi Hyun Choi, Seung Jin Kim, and Jung Bog Kim

Physics Education, Korea National University of Education, Chung-Buk, Korea republic

We consider counter-intuitive light pulses to transfer atoms coherently from the ground state to another ground state through the common excited state, lambda-type configuration [1]. We initially prepared field free cold ^{87}Rb atoms in the ground state of $5S_{1/2}$(F=1). And we detected the fluorescence by atoms in another ground state, $5S_{1/2}$(F=2), to measure amount of transferred atoms. We optimized experimental parameters - width of pulses, power of each pulse, delay time between two pulses, and the two photon detuning- until the effective Rabi frequency of overlapped area of two pulses corresponds to π which means total transfer.

Reference

[1] J. B. Kim, J. Lee, A. S. Choe, and Y. Rhee, "Geometrical representation of coherent-excitation methods using delayed and detuned lasers", Phys. Rev. A 55, pp. 3819-3825 (1997).

Quantum Ramsey interferometry

U. Dorner[1,2]

1. Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543
2. Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK
u.dorner1@physics.ox.ac.uk

The measurement of atomic transition frequencies with Ramsey interferometry has been established as an important tool, not only for general spectroscopic purposes but also to determine frequency standards on which atomic clocks are based on. Improvements of Ramsey interferometry via quantum effects are therefore highly desirable. Here we present methods for quantum enhanced Ramsey-type interferometry using trapped ions or neutral atoms which employ highly non-classical probe-states and decoherence free subspaces [1]. Our methods drastically improve the measurement uncertainty beyond what is possible classically in the presence of experimental noise and tolerate faulty detection and significantly imperfect state preparation. They are therefore feasible with current experimental technology and can lead to improved spectroscopic methods with important applications in metrology.

Reference

[1] U. Dorner, *Quantum frequency estimation with trapped ions and atoms*, New J. Phys. **14**, 043011 (2012).

The generation of entangled matter waves

B. Lücke[1], M. Scherer[1], J. Kruse[1], L. Pezzé[2], F. Deuretzbacher[3], P. Hyllus[4], O. Topic[1], J. Peise[1], W. Ertmer[1], J. Arlt[5], L. Santos[3], A. Smerzi[2], and C. Klempt[1,*]

1. Institut fürQuantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany
2. INO, CNR, and European Laboratory for Non-Linear Spectroscopy (LENS), 50125 Firenze, Italy
3. Institut für Theoretische Physik, Leibniz Universität Hannover, 30167 Hannover, Germany
4. Department of Theoretical Physics, The University of the Basque Country, 48080 Bilbao, Spain
5. QUANTOP, Institut for Fysik og Astronomi, Aarhus Universitet, 8000 Arhus C, Denmark
**klempt@iqo.uni-hannover.de*

The concept of entanglement has evolved from a controversial building block of quantum mechanics to the basic principle of many highly topical applications. In optics, parametric down-conversion in nonlinear crystals has become one of the standard methods to generate entangled states of light. Bose-Einstein condensates of atoms with non-zero spin provide a mechanism analogous to parametric down-conversion. The presented process acts as a two-mode parametric amplifier and generates two clouds with opposite spin orientation consisting of the same number of atoms. At a total of 10000 atoms, we observe a squeezing of the number difference of -7 dB below shot noise, including all noise sources [1]. As a first application, we demonstrate that the created state is useful for precision interferometry. We show that its interferometric sensitivity beats the standard quantum limit, the ultimate limit of unentangled states.

Reference

[1] B. Lücke, M. Scherer, J. Kruse, L. Pezzé, F. Deuretzbacher, P. Hyllus, O. Topic, J. Peise, W. Ertmer, J. Arlt, L. Santos, A. Smerzi, and C. Klempt, "Twin matter waves for interferometry beyond the classical limit", Science 334, 773 (2011).

An optical ionizing time-domain matter-wave interferometer

Philipp Haslinger[1,*], Nadine Dörre[1], Philipp Geyer[1], Jonas Rodewald[1], Stefan Nimmrichter[1], Klaus Hornberger[2], and Markus Arndt[1]

1. Vienna Center of Quantum Science and Technology (VCQ), University of Vienna, Faculty of Physics Boltzmanngasse 5, A-1090 Vienna, Austria
2. Universität Duisburg; Lotharstraße 21, 47057 Duisburg, Germany
**philipp.haslinger@univie.ac.at*

We discuss an all-optical Talbot-Lau interferometer for nanoparticles which consists of 3 pulsed VUV laser gratings [1]. The short laser pulse duration of about 7 ns allows us to address the particles in the time domain, which is a new concept for interferometry of complex matter. The interferometer uses pulsed standing laser light waves as diffracting structures. The light pulses can act as absorptive gratings for matter waves, as soon as the wavelength and laser intensity suffice to photo-ionize each particle with almost certainty in the vicinity of an anti-node of the standing light wave. In contrast to material masks, such gratings can be operated in a pulsed mode, which makes the motion of the particles negligible, in many cases. This establishes a new kind of velocity independent interferometer for molecules and clusters, which has the potential to interfere particles up to 10^6amu and more. This will be relevant for testing spontaneous quantum localization models [2].

References

[1] Nimmrichter S., *et al.*, *New J Phys.*, **13**, 075002 (2011).
[2] Nimmrichter S., *et al.*, *Phys. Rev. A*, **83**, 043621 (2011).

High-sensitivity large area atomic gyroscope

Matthieu Meunier, Thomas Lévêque, Christine Guerlin, Carlos Garrido Alzar, and Arnaud Landragin*

Laboratoire Systèmes de Référence Temps-Espace, Observatoire de Paris, CNRS et UPMC, Paris, France
**arnaud.landragin@obspm.fr*

SYRTE has previously built and extensively characterized a six-axis atom inertial sensor [1,2]. In particular, the uses of a four pulse sequence gyroscope and large momentum transfer beam splitter to enhance its area were investigated [3]. A new interferometer has now been developed at SYRTE based on these study, allowing a 300-fold increased area and enhanced scaling to the rotation; it should in addition allow for more robust large momentum transfer. Details of the architecture and preliminary characterizations will be presented. This very high sensitivity opens important perspectives in particular for fundamental physics, allowing for example improved tests of atom neutrality.

References

[1] B. Canuel *et al.*, "Six-axis inertial sensor using cold-atom interferometry", Phys. Rev. Lett. **97**, 010402 (2006).
[2] A. Gauguet *et al.*, "Characterization and limits of a cold atom Sagnac interferometer", Phys. Rev. A **80**, 063604 (2009).
[3] T. Lévêque *et al.*, "Enhancing the area of a Raman atom interferometer using a versatile double-diffraction technique", Phys. Rev. Lett. **103**, 080405 (2009).

Design of novel cold atom gravimeter integrated on chip and study of its theoretical performances

Mahdi Ammar[1,3,*], Landry Huet[1,2], Jérôme Estève[3], Chris Westbrook[4], Isabelle Bouchoule[4], Jean-Paul Pocholle[1], Jakob Reichel[3], Christine Guerlin[1,5], and Sylvain Schwartz[1]

1. Thales Research and Technology, 1 avenue Augustin Fresnel, 91767 Palaiseau, France
2. Thales Underwater Systems, 525 route des Dolines, BP 157, 06903 Sophia-Antipolis, France
3. Laboratoire Kastler-Brossel, Ecole Normale Supérieure, 24 Rue Lhomond, 75005 Paris, France
4. Laboratoire Charles-Fabry Institut d'Optique, Avenue Augustin Fresnel, 91127 Palaiseau, France
**mahdi.ammar@thalesgroup.com*

We propose a new design of a cold atom gravimeter integrated on chip. The chosen architecture of the sensor is to first manipulate coherently the internal states of the atoms, the ground-state hyperfine levels | F=1,m_F = -1> and | F=2,m_F = 1>, than to use microwave near-fields on atom chip to generate state-depend potentials. This technique was demonstrated with a Bose-Einstein Condensate (BEC) [1] might be applied also to thermal atoms which will cut-down atoms interactions. Above all, it reduces the detection to simple measures of fluorescence, more effective than imaging techniques. We have studied theoretically the various physical factors limiting the ultimate performances of such an inertial sensor and we propose to demonstrate soon an experimental proof of principle.

Reference

[1] Böhi *et al.*, Nat. Phys. **5**, 592 (2009).

Suppression of the blackbody radiation shift in atomic clocks

V. I. Yudin[1,2,3], A. V. Taichenachev[1,2], A. M. Tumaikin[1], D. V. Brazhnikov[1,2,*], S. N. Bagayev[1,2,3], M. V. Okhapkin[1], Chr. Tamm[4], E. Peik[4], N. Huntemann[4], T. E. Mehlstäubler[4], and F. Riehle[4]

1. Institute of Laser Physics SB RAS, Novosibirsk, Russia
2. Novosibirsk State University, Novosibirsk, Russia
3. Novosibirsk State Technical University, Novosibirsk, Russia
4. Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
**LLF@laser.nsc.ru*

We develop a concept of atomic clocks where the blackbody radiation shift and its fluctuations can be suppressed by 1-3 orders of magnitude independent of the environmental temperature. The suppression is based on the fact that in a system with two accessible clock transitions (with frequencies ν_1 and ν_2) which are exposed to the same thermal environment, there exists a “synthetic” frequency $\nu_{syn} \propto (\nu_1 - \varepsilon_{12}\nu_2)$ largely immune to the blackbody radiation shift. For example, in the case of $^{171}Yb^+$ it is possible to create a synthetic-frequency-based clock in which the fractional blackbody radiation shift can be suppressed to the level of 10^{-18} in a broad interval near room temperature (300 ± 15 K). We also propose a realization of our method with the use of an optical frequency comb generator stabilized to both frequencies ν_1 and ν_2, where the frequency ν_{syn} is generated as one of the components of the comb spectrum. The work was supported by QUEST, DFG/RFBR (10-02-91335), RFBR (10-02-00406, 11-02-00775, 11-02-01240), Minobrnauka (GK 16.740.11.0466), RAS, Presidium of the SB RAS. D.V.B. was also supported by the Presidential Grant (MK-3372.2012.2).

Magic radio-frequency dressing of nuclear spins in optical atomic clocks

Thomas Zanon-Willette[1,2,*], Emeric de Clercq[3], and Ennio Arimondo[4]

1. UPMC Univ. Paris 06, UMR 7092, LPMAA, 4 place Jussieu, case 76, 75005 Paris, France
2. CNRS, UMR 7092, LPMAA, 4 place Jussieu, case 76, 75005 Paris, France
3. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 avenue de l'Observatoire, 75014 Paris, France
4. Dipartimento di Fisica "E. Fermi", Università di Pisa, Lgo. B. Pontecorvo 3, 56122 Pisa, Italy
**thomas.zanon@upmc.fr*

We investigate the radio-frequency quantum engineering of nuclear spins for an ultra narrow optical clock transition based on the fermionic ^{87}Sr, ^{171}Yb and ^{199}Hg species. A Zeeman-insensitive optical clock transition is produced by dressing nuclear quantum spin with a non resonant radio-frequency (r.f.) field. Particular ratios between the r.f. driving amplitude and the non resonant r.f. field lead to "magic" weak values of the static field where a net cancelation of the differential Zeeman shift with a 100 % reduction of first order fluctuation are observed within a relative uncertainty below 10^{-18} level.

Atomic clocks Mo-014

Optical pumping and spin polarisation in a Cs atomic fountain

K. Szymaniec[1,*], H. R. Noh[2], S. E. Park[3], and A. Takamizawa[4]

1. National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK
2. Department of Physics, Chonnam National University, Gwangju 500-757, Korea
3. Korea Research Institute of Standards and Science, Daejeon 305-600, Korea
4. National Metrology Institute of Japan (NMIJ-AIST), Tsukuba, Ibaraki 305-8563, Japan
**krzysztof.szymaniec@npl.co.uk*

We present a detailed study of optical pumping in a freely evolving cloud of cold Cs atoms launched in an atomic fountain. With π-polarised pumping light tuned to an $F \rightarrow F' = F$ transition, a high degree of atomic spin polarisation was achieved by accumulation of the population in the $m_F = 0$ sublevel of the ground state. Such a scheme has been proposed and demonstrated for thermal beam clocks [1], but the technique has not been widely implemented for normal operation. In the case of cold atoms the random scattering of photons associated with optical pumping significantly increases the temperature of the atomic ensemble. We have investigated theoretically and experimentally the dynamics of the pumping process and the related heating mechanism and considered factors limiting the achievable spin polarisation. This technique has been implemented in a Cs fountain clock, giving a nearly five-fold increase in the useful cold atom signal.

Reference

[1] G. Avila, V. Giordano, V. Candelier, E. de Clercq, G. Theobald and P. Cerez, "State selection in a caesium beam by laser-diode optical pumping", Phys. Rev. A **36**, 3719 (1987).

A mobile atomic frequency standard with cold atoms

Stella Torres Müller[1,2,*], Rodrigo Duarte Pechoneri[1], Felipe Arduini Otoboni[1], Jair de Martin Júnior[1], Denis Henrique Neves[1], Vanderlei Salvador Bagnato[2], and Daniel Varela Magalhães[1]

1. Departamento de Engenharia Mecânica, EESC/Universidade de São Paulo, São Carlos, Brazil
2. Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, Brazil
**stella@ifsc.usp.br*

We have constructed a compact frequency standard using an intra-cavity sample cold cesium atoms. The results show the potential use of clocks with this operation if compared to a cesium beam standard, since all the steps are sequentially performed in the same position of space. Due to the fact that the atomic standard is based on an expanding cloud of atoms, it has no stringent size limitations and one can imagine the possibility of a clock even more compact. For the next step of our ongoing project we are developing a system containing all the laser sources, microwave source and cavity in a single metallic block. The mobile atomic standard based on cold atoms can be an important contribution to a primary standard of high relevance, and a possible strategic product with a broad range of applications.

Reference

[1] Müller, S. T. *et al.* "Compact Frequency Standard Based on an Intra-cavity Sample Cold Cesium Atoms", J. Opt. Soc. Am. B **28** n11, pp. 2592-2596 (2011).

Laser excitation of 8-eV electronic states in Th+: a first pillar of the electronic bridge toward excitation of the Th-229 nucleus

O. A. Herrera-Sancho, M. V. Okhapkin, Chr. Tamm, and E. Peik

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

The possibility to realize a nuclear clock based on laser excitation of the isomeric state in Th-229 [1,2] has motivated experiments with thorium ions in solids and in ion traps. To facilitate the search for the nuclear transition within a wide uncertainty range about 8 eV, we investigate two-photon excitation in the dense electronic level structure of Th^+, which enables the nuclear excitation via a resonantly enhanced electronic bridge process [3]. In our experiment, the Th^+ resonance line at 402 nm from the $(6d^2 7s)J=3/2$ ground state to the $(6d7s7p)J=5/2$ state is driven as the first excitation step [4]. Using nanosecond laser pulses in the 250-nm wavelength range for the second step of a two-photon excitation, we have observed several previously unknown levels of Th^+ around 8 eV.

References

[1] E. Peik, Chr. Tamm, Europhys. Lett. **61**, 181 (2003).
[2] C. J. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012).
[3] S. G. Porsev, V. V. Flambaum, E. Peik, Chr. Tamm, Phys. Rev. Lett. **105**, 182501 (2010).
[4] O. A. Herrera-Sancho *et al.*, Phys. Rev. A **85**, 033402 (2012).

Portable frequency standard with strontium in optical lattices

Ole Kock, Steven Johnson, Yeshpal Singh*, and Kai Bongs

School of Physics and Astronomy, University of Birmingham, Edgbaston Park Road, Birmingham B15 2TT, UK
**y.singh.1@bham.ac.uk*

The unprecedented accuracy in time promises new applications like relativistic geodesy for exploration of oil and minerals, fundamental tests of general relativity and synchronization for long base line astronomical interferometry. In fact very recently, space has also opened up as a new avenue for precision measurements based on cold atoms. We are setting up a mobile frequency standard based on strontium (Sr) in a blue detuned optical lattice. We have a 2D-3D MOT (magneto-optical trap) setup where initially cooled atoms in 2D are collected in the 3D MOT. Very recently we have observed an effect of our 2D MOT on our 3D MOT where atom number increases approximately by a factor of 10. However, these are only preliminary results and a thorough optimization as well as characterization will be done in due course of time. An up to date progress on our activities will be presented.

A neutral mercury optical lattice clock

R. Tyumenev, Z. Xu, L. Yi, S. Mejri, Y. Le Coq, J. J. McFerran, and S. Bize*

LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, F-75014 Paris, France
**sebastien.bize@obspm.fr*

Optical lattice clocks [1] are among the most accurate clocks to date and have a huge potential for further improvement, owing to their unique possibility to combine the advantage of the Lamb-Dicke regime spectroscopy (drastic reduction of shifts associated with the dynamics of external variables) together with the possibility of probe a large number of quantum absorbers simultaneously. Among atoms studied in optical lattice clocks, mercury has very low sensitivity to blackbody radiation, making it an excellent candidate for achieving accuracies in the low 10^{-18}, for testing the stability of natural constants or for demonstrating new applications, such as relativistic geodesy. We will report on our first and so far only operation of an Hg optical lattice clock. This includes the first experimental determination of the magic wavelength [2] and the first absolute frequency measurements down to the mid-10^{-15} range [3]. These results demonstrate that the considerable challenge due to the need for deep-UV laser light can be met to make a new clock with extreme accuracy.

References

[1] H. Katori, *Optical lattice clocks and quantum metrology*, Nat. Photon. 5, 203 (2011).
[2] L. Yi *et al.*, *Optical Lattice Trapping of ^{199}Hg and Determination of the Magic Wavelength for the Ultraviolet $^1S_0 - {}^3P_0$ Clock Transition*, Phys. Rev. Lett 106, 073005 (2011).
[3] J. J. McFerran *et al.*, *Neutral Atom Frequency Reference in the Deep Ultraviolet with a Fractional Uncertainty* = 5.7×10^{-15}, Phys. Rev. Lett. 108, 183004 (2012).

^{87}Sr lattice clock as a reference for the characterization of a Ca^+ ion clock

H. Hachisu[1,*], K. Matsubara[1], S. Nagano[1], Y. Li[1], A. Nogami[1], A. Yamaguchi[1], C. Locke[1], K. Hayasaka, and T. Ido[1,2]

1. National Institute of Information and Communications Technology, Tokyo, Japan
2. JST-CREST, Tokyo, Japan
**hachisu@nict.go.jp*

Instability and systematic shifts of optical clocks are rapidly evaluated by referring another stable optical clock. Following an all-optical frequency comparison of two remote ^{87}Sr lattice clocks (one at NICT and the other in University of Tokyo) in 10^{-16} level [1], we conducted an in-laboratory frequency comparison between a single calcium ion clock and the ^{87}Sr lattice clock. The ^{87}Sr lattice clock in NICT has total systematic uncertainty of 5×10^{-16} and the stability reaches 5×10^{-16} in 1000 s. Thus the lattice clock worked as an optical frequency reference for the evaluation of our lately improved Ca^+ clock, which currently equips a magnetic shield to reduce Zeeman shift [2]. The frequency ratio of $f\,(Ca^+)\,/\,f\,(Sr)$ obtained with the optical comparison has statistical uncertainty of 1×10^{-15} in 1000 s and is consistent with separate absolute frequency measurements based on International Atomic Time, where the 10^{-15} level of calibration is notified after a month's latency.

References

[1] A. Yamaguchi *et al.*, "Direct comparison of distant optical lattice clocks at the 10^{-16} uncertainty", Appl. Phys. Express, **4**, pp. 082203 (2011).
[2] K. Matsubara *et al.*, "Frequency measurement of the optical clock transition of $^{40}Ca^+$ ions with an uncertainty of 10^{-14} level", Appl. Phys. Express, **1**, pp. 067011 (2008).

Precise measurement of vibrational frequencies of ^{174}Yb^{6}Li molecules in an optical lattice; toward the test of variance in m_p/m_e

Masatoshi Kajita[1,*], Geetha Gopakumar[2], Minori Abe[2], and Masahiko Hada[2]

1. Nat. Inst. Info. Commu. Tech,.Koganei, Tokyo, Japan
2. Tokyo Metropolitan U., Hachioji, Tokyo, Japan
**kajita@nict.go.jp*

Transition frequencies of cold molecules must be accurately evaluated to test the variance in the proton-to-electron mass ratio. Measurement of the $X^2\Sigma$ $(v,N) = (0,0)$-> (1,0),(2,0),(3,0),(4,0) transition frequencies of optically trapped ^{174}Yb^{6}Li molecules are the promising method to achieve this goal [1]. ^{174}Yb^{6}Li molecules are produced via Feshbach resonance or optical association, and forced to the $(v,N) = (0,0)$ state by stimulated Raman transition. The Stark shift induced by trap laser is eliminated by choosing appropriate frequencies (magic frequency). For ^{174}Yb^{6}Li molecule, the magic frequency exists also in the far-off resonant area. Using this magic frequency, the Stark shift is less than 10^{-16} if the trap laser frequency is detuned from the magic frequency with 1 MHz. The transition is observed by Raman transition, using two lasers. Also the Stark shift induced by Raman lasers can be eliminated, because the Stark shifts induced by two Raman lasers cancel each other, when the magic frequency exists between both Raman laser frequecnies.

Reference

[1] M. Kajita *et al.*, "Elimination of the Stark shift from the vibrational transition frequency of optically trapped ^{174}Yb^{6}Li molecules", Phys. Rev. A **84**,022507 1-6 (2011).

Phase noise of an atom interferometer for equivalence principle test in space

Xi Chen, Fen Gao, Jin Wang, and Mingsheng Zhan*

State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics,Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China
Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
**mszhan@wipm.ac.cn*

High precision cold atom interferometers have important applications in many fundamental physics experiments[1]. Using dual-species atom interferometers to measure the gravity synchronously can make a precision test of the weak equivalence principle. Because ^{85}Rb and ^{87}Rb atoms have similar Raman laser wave vectors, many fluctuations and systematic errors can be eliminated in differential measurement. At the microgravity environment in space, the free evolution time can be greatly extended[2]. We analyze the differential phase noise of an ^{85}Rb-^{87}Rb dual specie atom interferometer in space environment in detail, and find that in typical experimental parameters, $\sigma_\eta=3.2\times10^{-13}$ could be reached per shot, and $\sigma_\eta=3.4\times10^{-15}$ after one day's integration.

References

[1] S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, "General relativistic effects in atom interferometry", Phys. Rev. D **78**, pp.042003 (2008).
[2] W. Ertmer, C. Schubert, T. Wendrich, *et al.*, "Matter wave explorer of gravity (MWXG)", Exp. Astron. **23**, pp.611–649(2009).

Towards realization of the E-P-R experiment for atoms created via molecular dissociation in pulsed supersonic beam

T. Urbańczyk[1,*], M. Strojecki[2], and J. Koperski[1]

1. Smoluchowski Institute of Physics, Jagiellonian University, Reymonta 4, 30-059 Krakow, Poland
2. Haber Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Niezapominajek 8, 30-239 Krakow, Poland
**ufkopers@cyf-kr.edu.pl*

An idea of realization of the Einstein-Podolsky-Rosen experiment for two spin-1/2 ^{111}Cd atoms will be presented. The concept is based on the proposal of Fry *et al.* formulated for ^{199}Hg [1]. In the presented experiment, the $^{111}Cd_2$ molecules are produced in a pulsed supersonic beam. Next, the $^{111}Cd_2$ molecules are irradiated by two laser pulses and dissociated in a process of stimulated Raman passage. As a result, two entangled ^{111}Cd atoms with anti-parallel nuclear spins are produced. Orientation of the nuclear spins is recorded using spin-state-selective two-photon excitation-ionization method [2]. Current status of the preparation stage of the experiment will be reported.
The project is financed by the National Science Centre (contract UMO-2011/01/B/ST2/00495).

References

[1] E. S. Fry, Th. Walther and S. Li, "Proposal for a loophole-free test of the Bell inequalities", Phys. Rev. A **52**, pp. 4381-4395 (1995).
[2] J. Koperski, M. Strojecki, M. Krośnicki and T. Urbańczyk, "Potentials of the $D^10_u^+$ (6^1S_0) and F^31_u(6^3P_2) electronic Rydberg states of Cd_2 from *ab initio* calculations and LIF excitation spectra", J. Phys. Chem. A **115**, pp. 6851-6860 (2011).

High precision atomic gravimetry with Bragg-based beam splitters

J. E. Debs[1,*], P. A. Altin[1], M. T. Johnsson[1], G. R. Dennis[1], S. S. Szigeti[1], G. McDonald[1], K. S. Hardman[1], S. Bennetts[1], C. C. Kuhn[1], H. Keal[1], R. P. Anderson[2], V. Negnevitski[2], L. D. Turner[2], J. D. Close[1], and N. P. Robins[1]

1. Dept. of Quantum Science, The Australian National University, Canberra, Australia
2. School of Physics, Monash University, Melbourne, Australia
**john.debs@anu.edu.au*

We present a gravimeter based on the use of Bragg diffraction to drive atomic beam splitters and mirrors. Traditionally, gravimeters based on cold atoms have used Raman transitions for the optical elements, a process that drives transitions between internal atomic states which are highly sensitive to environmental perturbations (e.g. see [1,2]).Here we show that atoms extracted from a magneto-optical trap with an accelerating optical lattice are a suitable source for a Bragg interferometer, allowing efficient beam splitting and separation of momentum states for detection. Our current device, based on a $T = 60$ms, $4\hbar$k interferometer, achieves a sensitivity of $\Delta g/g$ of 2×10^{-9} in 15 minutes. We discuss a number of improvements which should push this device into the μGal regime and beyond.

References

[1] A. Peters, K. Y. Chung, and S. Chu, *High-precision gravity measurements using atom interferometry.* Metrologia **38**, pp. 25-61 (2001).

[2] J. le Gouët, *et al.*, *Limits to the sensitivity of a low noise compact atomic gravimeter.* Appl. Phys. B **92**, pp. 133-144 (2008).

Thermal effects in the Casimir-Polder interaction

Athanasios Laliotis, Thierry Passerat de Silans, Marie-Pascale Gorza, Isabelle Maurin, Martial Ducloy, and Daniel Bloch*

Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris-Cité
and
CNRS, UMR 7538, 99 Avenue J-.B. Clément, F-93430 Villetaneuse, France
**daniel.bloch@univ-paris13.fr*

The long-range atom-surface interaction, of Casimir-Polder type, is a fundamental interaction, which modifies the electrodynamics corrections of atomic energy levels, as due to limiting conditions imposed by the surface. The realm of non-zero temperature corrections, which can be interpreted as a coupling of an atomic detector with the near-field of a blackbody radiator, has received little experimental attention, In the achievement of [1], a key point allowing the observation, was an amplification, in a long-distance situation, of thermal effects by a non-equilibrium situation (overheated surface, relatively to the remote environment). We are presently performing experiments at Cs(7D)/saphir interface in the near-field regime, and observe an increase of the atom-surface attraction with the temperature of equilibrium. We show also that in this near-field regime, a thermal disequilibrium does not amplify the interaction, solely governed by the surface temperature.

Reference

[1] J. M. Obrecht, M. Antezza, L. P. Pitaevskii, S. Stringari, E. A. Cornell*, Measurement of the Temperature Dependence of the Casimir-Polder Force*, Phys. Rev. Lett. **98,** 063201 (2007).

The *g*-factor of hydrogen- and lithiumlike silicon

Florian Köhler[1,2,*], Klaus Blaum[2,3], Wolfgang Quint[1,2], Sven Sturm[3,4], Anke Wagner[2,3], and Günter Werth[4]

1. GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
2. Fakultät für Physik und Astronomie, Ruprecht-Karls-Universität, Heidelberg, Germany
3. Max-Planck-Institut für Kernphysik, Heidelberg, Germany
4. Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany
**koehlef@uni-mainz.de*

Ultra-precise measurements of the gyromagnetic factor (*g*-factor) of a bound electron in highly charged medium-heavy ions provide a sensitive test of quantum electrodynamics in bound systems (BS-QED) under extreme conditions. To determine the *g*-factor the Larmor frequency and the free cyclotron frequency of a single ion are measured in a triple Penning-trap setup. The continuous Stern-Gerlach effect allows an indirect measurement of the Larmor frequency. The free cyclotron frequency is determined by the measurement of the three motional eigenfrequencies. In this context the *g*-factor of hydrogenlike silicon $^{28}Si^{13+}$ has been measured with a relative uncertainty of $5 \cdot 10^{-10}$ representing the most stringent test of BS-QED in strong fields [1]. Two *g*-factor measurements of a hydrogenlike and a lithiumlike system with the same nucleus offer a test of the electron-electron interaction calculations. For this reason the *g*-factor measurementof $^{28}Si^{11+}$ is currently under progress. The measurement procedure and results are presented.

Reference

[1] S. Sturm *et al.*, Phys. Rev. Lett. **107**, 023002 (2011).

New perspectives on the search for a parity violation effect in chiral molecules

Sean Tokunaga, Frédéric Auguste, Clara Stoeffler, Alexandre Shelkovnikov,
Christophe Daussy, Benoît Darquié*, Anne Amy-Klein, and Christian Chardonnet

Laboratoire de Physique des Lasers, UMR7538 CNRS/Université Paris 13, Villetaneuse, France
**benoit.darquie@univ-paris13.fr*

Parity violation (PV) effects have so far never been observed in chiral molecules. Originating from the weak interaction, PV should lead to frequency differences in the rovibrational spectra of the two enantiomers of a chiral molecule. However the weakness of the effect represents a very difficult experimental challenge. We propose to compare the rovibrational spectra (around 10 μm) of two enantiomers, recorded using the ultra-high resolution spectroscopy technique of Doppler-free two-photon Ramsey fringes in a supersonic molecular beam. With an alternate beam of left- and right-handed molecules and thanks to our expertise in the control of the absolute frequency of the probe CO_2 lasers, we should reach a fractional sensitivity better than 10^{-15}, on the frequency difference between enantiomers [1].

We will review our latest results on the high-resolution spectroscopy, either in cell or in a supersonic beam, of methyltrioxorhenium [2], an achiral test molecule from which our collaborators are currently synthesizing chiral derivatives fulfilling all the requirements for the PV test.

References

[1] B. Darquié *et al.*, *Progress Toward the First Observation of Parity Violation in Chiral Molecules by High-Resolution Laser Spectroscopy*, Chirality **22**, pp. 870-884 (2010).
[2] C. Stoeffler *et al.*, *High resolution spectroscopy of methyltrioxorhenium: towards the observation of parity violation in chiral molecules*, Phys. Chem. Chem. Phys. **13**, pp. 854-863 (2011).

Heralded entanglement between widely separated atoms

J. Hofmann[1,2], M. Krug[1], N. Ortegel[1], W. Rosenfeld[1,2], M. Weber[1,*], and H. Weinfurter[1,2]

1. Fakultät für Physik, Ludwig-Maximilians-Universität München, Germany
2. Max-Planck-Institut für Quantenoptik, Garching, Germany
**markusweber@lmu.de*

Entanglement is the essential feature of quantum mechanics. Its importance arises from the fact that observers of two or more entangled particles will find correlations in their measurement results, which can not be explained by classical statistics. In order to make it a useful resource for, e.g., scalable long-distance quantum communication, heralded entanglement between distant massive quantum systems is necessary. Here we report on the generation and analysis of heralded entanglement between spins of two single Rb-87 atoms trapped independently 20 meters apart [1]. We observe an entanglement fidelity of 0.82 which is high enough to even violate a Bell inequality. This achievement together with our recently developed ultra-fast and highly efficient single atom detector [2] form the starting point for new experiments in quantum information science and for a first loophole-free test of Bell's inequality [3,4].

References

[1] J. Hofmann, M. Krug, N. Ortegel *et al.*, submitted to Science (2012).
[2] F. Henkel, M. Krug, J. Hofmann *et al.*, Phys. Rev. Lett. **105**, 253001 (2010).
[3] J. Volz, M. Weber, D. Schkenk *et al.*, Phys. Rev. Lett. **96**, 030404 (2006).
[4] W. Rosenfeld, M. Weber *et al.*, Adv. Sci. Lett. **2**, 469 (2009).

Determination of the fine structure constant and test of the quantum electrodynamics

Rym Bouchendira, Pierre Cladé, Saïda Guellati, François Nez, and François Biraben

Laboratoire Kastler Brossel, Université Pierre et Marie Curie/ENS/CNRS, Paris France
pierre.clade@spectro.jussieu.fr

We present a measurement of the ratio h/m_{Rb} between the Planck constant and the mass of ^{87}Rb atom using atom interferometry. A new value of the fine structure constant, with a relative uncertainty of 6.6×10^{-10}, is deduced[1]: $\alpha^{-1} = 137.035\ 999\ 037\ (91)$. Using this determination, we obtain a theoretical value of the electron anomaly $a_e = 0.001\ 159\ 652\ 181\ 13\ (84)$ which is in agreement with the experimental measurement of Gabrielse ($a_e = 0.001\ 159\ 652\ 180\ 73\ (28)$). The comparison of these values provides the most stringent test of the QED. Moreover, the precision is large enough to verify for the first time the muonic and hadronic contributions to this anomaly.

Using this method, it seams possible to further reduce systematic effects and improve the precision of the measurement by a factor 7.

Reference

[1] Rym Bouchendira, Pierre Cladé, Saïda Guellati-Khélifa, Francois Nez, and Francois Biraben, *New determination of the fine structure constant and test of the quantum electrodynamics*, Phys. Rev. Lett. **106** (2011), no. 8, 080801.

Development of a double MOT system and spectroscopy of iodine molecule at 718 nm toward the electron EDM measurement

Kenichi Harada[1,*], Takatoshi Aoki[2], Tomohiro Hayamizu[1], Saki Ezure[1], Masatoshi Itoh[1], Hidetomo P. Yoshida[3], Hirokazu Kawamura[1], Tomoya Sato[1], Tomohiro Kato[1], Huliyar S. Nataraj[1], and Yasuhiro Sakemi[1]

1. Cyclotron and Radioisotope Center, Tohoku University, Japan
2. University of Tokyo, Japan
3. Research Center for Nuclear Physics, Osaka University, Japan
**harada@cyric.tohoku.ac.jp*

Search for the permanent electric dipole moment (EDM) of the elementary particles has been of considerable interest in the recent decades. Laser cooling and trapping technique reduces the systematic error of the EDM measurement due to the $v \times E$ effect. Further, it dramatically elongates the interaction time with an external electric field by two or three orders of magnitude, when compared to the conventional atomic beam experiments. This longer interaction time substantially improves the sensitivity of the EDM measurement. Additionally, Francium (Fr) being the heaviest alkali atom has a large enhancement factor of about 900. The laser cooled Fr atoms are promising for the measurement of the e-EDM. As the Fr production requires the cyclotron operation which being expensive for a continuos operation, we work with Rb atoms and the Rb beam is utilized for optimizing the operation parameters of the entire apparatus. We have developed a double magneto-optical trap (MOT) system and trapped Rb atoms. We have also observed the saturated absorption spectra of iodine molecules at 718 nm. The high resolution signal is used to stabilize the laser frequency to the D2 transition of Fr atom.

Direct measurement of the proton magnetic moment

Jack DiSciacca, Kathryn Marable, Mason Marshall, and Gerald Gabrielse

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

We report the first direct measurement of the proton magnetic moment at the part per million level [1]. Using a single proton in a Penning trap, this demonstrates the first method that should work as well with an antiproton ($\bar{p}$) as with a proton (p). This opens the way to measuring the $\bar{p}$ magnetic moment (whose uncertainty has essentially not been reduced for 20 years) at least 10^3 times more precisely.

Reference

[1] J. DiSciacca and G. Gabrielse, "Direct Measurement of the Proton Magnetic Moment", Phys. Rev. Lett. **108**, 153001 (2012).

Intracavity two-photon spectroscopy and a potential hand-size secondary frequency standard

Chien-Ming Wu, You-Huan Chen, Tze-Wei Liu, and Wang-Yau Cheng*

National Central University Jongli, Taoyuan 32001, Taiwan
**wycheng@ncu.edu.tw*

We report an intracavity scheme for diode laser based two-photon spectroscopy [1]. To demonstrate generality, three ^{133}Cs hyperfine transition groups of different wavelengths are shown. For the 6S-6D transitions, we achieved 10^2 times better signal-to-noise ratio than previous work[1] with 10^{-3} times less laser power, revealing some previously vague and unobserved spectra. Possible mutual influences between the two-photon absorber and laser cavity were investigated for the first time to our knowledge, which leads to the application of a reliable and hand-sized optical frequency reference. Our approach is applicable for most of the two-photon spectroscopy of alkali atoms. We currently measured the absolute frequencies of all the two-photon hyperfine transitions. The reproducibility of measured frequencies (within 3 kHz, two months) is encouraging for considering the application of our scheme to be a hand-size diode-laser based secondary frequency standard.

Reference

[1] Y.-Y. Chen, T.-Wei Liu, C.-M. Wu, C.-C. Lee, C.-K. Lee and W.-Y. Cheng, *"High-resolution ^{133}Cs 6S-6D, 6S-8S two-photon spectroscopy using an intracavity scheme"*,Opt. lett. **36**, 76 (2011).

Towards the absolute calibration of the reference line for muonium 1S-2S spectroscopy

Isaac Fan[1,*], Yu-Yuan Lee[1], Hsuan-Chen Chen[2], Shih-En Chen[1], and Li-Bang Wang[1]

Jow-Tsong Shy[1,2], and Yi-Wei Liu[1,†]

1. Department of Physics, Nat'l. Tsing Hua Univ., Hsinchu City, 30013 Taiwan (R.O.C)
2. Institute of Photonics Technology, Nat'l. Tsing Hua Univ., Hsinchu City, 30013 Taiwan (R.O.C)
**ifan@phys.nthu.edu.tw, † ywliu@phys.nthu.edu.tw*

A muonium atom (*Mu*) is a bound state formed by a muon (μ^+) and an electron, offering a structureless two-body leptonic system whose energies can be evaluated with high accuracies by the bound-state QED. The $1S-2S$ transition of *Mu* is of particular importance because the muon mass and the ground-state Lamb shift contribution can be derived from it imposing a cross-check on the recent muonic hydrogen $2S-2P$ Lamb shift measurement in which a smaller than expected proton size was found [1]. The current experimental resolution of *Mu* Δv_{1S-2S} is limited by (a) the flux of *Mu* in vacuum, (b) the frequency chirps in the pulsed light source, and (c) the precision of the reference line. In this conference, we present our effort in improving the precision of the 732 nm reference line in molecular iodine that is suitable for the *Mu* Δv_{1S-2S} spectroscopy.

Reference

[1] R. Pohl *et al. The size of the proton*, Nature **466**, pp. 213-217 (2010).

Imaging the build-up of a quantum interference pattern of massive molecules

Thomas Juffmann[1], Adriana Milic[1], Michael Müllneritsch[1], Peter Asenbaum[1], Alexander Tsukernik[2], Jens Tüxen[3], Marcel Mayor[3], Ori Cheshnovsky[2], and Markus Arndt[1,*]

1. Vienna Center of Quantum Science and Technology, Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria
2. The Center for Nanoscience and Nanotechnology, Tel Aviv University, 69978 Tel Aviv, Israel
3. Department of Chemistry, University of Basel, St. Johannsring 19, 4056 Basel, Switzerland
**contact markus.arndt@univie.ac.at*

New experiments allow us for the first time to visualize the gradual emergence of a deterministic far-field matter-wave diffraction pattern from stochastically arriving single molecules. A slow molecular beam is created via laser evaporation of the molecules from a glass window. The molecules traverse an ultra-thin nanomachined grating at which they are diffracted and quantum delocalized to more than 100 µm before they are captured on a quartz plate at the interface between the vacuum chamber and a self-built fluorescence microscope. Fluorescence imaging provides us with single molecule sensitivity and we can determine the position of each molecule with an accuracy of 10 nm. This new setup is a textbook demonstration but it also enables quantitative explorations of the van der Waals forces between molecules and material gratings. An extrapolation of our present experiments to even thinner gratings is expected to also enlarge the range of nanoparticles that are accessible to advanced quantum experiments.

Reference

[1] Juffmann *et al.*, "Real-time single-molecule imaging of quantum interference", Nature Nanotechnology 7, 297-300 (2012).

Electric dipole moments and parity violation in atoms and molecules

V. V. Flambaum

School of Physics, University of New South Wales, Sydney 2052, Australia
v.flambaum@unsw.edu.au

This presentation is based on the following recent publications [1, 2, 3, 4, 5]:

References

[1] V. V. Flambaum, A. Kozlov, *Extension of the Schiff theorem to ions and molecules*, Phys. Rev. A **85**, pp. 022505-3 (2012).
[2] V. A. Dzuba, V. V. Flambaum, C. Harabati, *Relations between matrix elements of different weak interactions and interpretation of the PNC and EDM measurements in atoms and molecules*, Phys. Rev. A **85**, pp. 022505-3 (2012).
[3] A. Borschevsky, M. Ilias, V. A. Dzuba, K. Beloy, V. V. Flambaum, and P. Schwerdtfeger, *Relativistic ab initio calculations of the P-odd interaction constant W_A in diatomic molecules* , Phys. Rev. A **85**, pp. 052509-7 (2012).
[4] V. A. Dzuba, V. V. Flambaum, *Parity nonconservation in hyperfine transitions*, Phys. Rev. A **85**, pp. 012515-5 (2012).
[5] V. A. Dzuba, V. V. Flambaum, *Calculation of nuclear-spin-dependent parity nonconservation in s-d transitions of Ba+, Yb+ and Ra+ ions*, Phys. Rev. A **83**, pp. 052513-5 (2011).

Precision magnetometry with spin-polarized xenon: toward a Neutron EDM Co-magnetometer

Skyler Degenkolb*, Aaron Leanhardt, and Tim Chupp

University of Michigan, Ann Arbor, Michigan 48109
**sdegen@umich.edu*

Atomic magnetometer sensitivity is a limiting factor in precision measurements, medical imaging, and industrial applications. In particular, searches for permanent electric dipole moments (EDMs) require sensitive magnetometers which interact minimally with the primary samples. Techniques based on spin-polarized gases have been very successful in this capacity, but it remains difficult to perform correct spatial and temporal averages. Previous magnetometers (e.g. alkalis or ^{199}Hg) also suffer from material problems at the high voltages and low temperatures common in EDM experiments. We propose as a remedy real-time optical magnetometry based on spectroscopy of two-photon transitions in spin-polarized ^{129}Xe. Thermal, diffusive, and dielectric properties of xenon allow sensitive measurements in a wide range of electromagnetic field strengths and sample volumes, while long spin coherence times and a low neutron capture cross-section are favorable in neutron EDM experiments. We report on preliminary work validating the technique in ^{171}Yb and a parallel effort measuring the ^{129}Xe EDM, and survey applications to contemporary neutron EDM measurements.

Large scale CIV3 calculations of fine-structure energy levels and lifetimes in co XIV

G. P. Gupta[1,*] and A. Z. Msezane[2]

1. Department of Physics, S. D. (Postgraduate) College, Muzaffarnagar – 251 001
(Affiliated to Chowdhary Charan Singh University, Meerut - 250 004), India
2. Department of Physics and Center for Theoretical Studies of Physical Systems,
Clark Atlanta University, Atlanta, Georgia 30314, USA
**g_p_gupta1@yahoo.co.in*

Large scale CIV3 calculations of excitation energies from ground state as well as of oscillator strengths and radiative decay rates for all electric-dipole-allowed and intercombination transitions among the fine-structure levels of the terms belonging to the $(1s^22s^22p^6)3s^23p^2$, $3s3p^3$, $3p^4$, $3s^23p3d$, $3p^33d$, $3s3p3d^2$, $3s^23d^2$, $3s3p^23d$, $3s3p^24s$, $3s^23p4s$, $3s^23p4p$, $3s^23p4d$ and $3s^23p4f$ configurations of Co XIV, are performed using very extensive configuration-interaction (CI) wavefunctions. The relativistic effects in intermediate coupling are incorporated by means of the Breit-Pauli Hamiltonian. Our calculated excitation energies and the radiative lifetimes of the fine-structure levels are in excellent agreement with the data compiled by NIST and the experimental lifetimes, wherever available.

Relativistic effects on the hyperfine structures of $2p^4(^3P)3p\ ^2D^o$, $^4D^o$, $^2P^o$ in F I

Messaoud Nemouchi[1,*], Jiguang Li[2], Thomas Carette[3], and Michel Godefroid[2]

1. Faculté de Physique, Laboratoire d'Électronique Quantique, USTHB, Algiers, Algeria
2. Chimie Quantique et Photophysique, Université Libre de Bruxelles, B-1050 Brussels, Belgium
3. Department of Physics, Stockholm University, SE-10691Stockholm, Sweden
**mnemouchi@usthb.dz*

In this work, the hyperfine interaction constants of the $2p^4(^3P)3p\ ^2D^o$, $^4D^o$ and $^2P^o$ levels in neutral fluorine are investigated theoretically. Large-scale calculations are carried out using the atsp2k [1] and grasp2k [2] packages based on the multiconfiguration Hartree-Fock (MCHF) and Dirac-Fock (MCDF) methods, respectively. In both non-relativistic and relativistic models, the set of many-electron states selected to form the total wave function is constructed systematically using the “single and double multireference” approach. In the framework of MCHF, the relativistic effects are taken into account, either in the Breit-Pauli (BP) approximation using the MCHF orbitals or through relativistic configuration interaction (RCI) calculations, in which the non-relativistic one-electron basis is converted to Dirac spinors using the Pauli approximation [3]. The MCHF-BP, RCI and MCDF results are in satisfactory agreement with experiments, but differ from the MCHF calculations. It shows that, in a system like F I, relativistic effects can be crucial but do not require the use of a fully relativistic method.

References

[1] C. F. Fischer *et al.*, Comput. Phys. Comm. **176**, pp. 559-579 (2007).
[2] P. Jönsson, X. He, C. F. Fischer and I. P. Grant , Comput. Phys. Comm. **176**, pp. 597-692 (2007).
[3] T. Carette and M. R. Godefroid, Phys. Rev. A **83**, pp. 062505-062514 (2011).

Dual frequency comb spectroscopy in the near IR

F. Zhu[1], T. Mohamed[1,2], J. Strohaber[1], A. A. Kolomenskii[1], and H. A. Schuessler[1,2,*]

1. Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
2. Science Department, Texas A&M University at Qatar, Doha 23874, Qatar
**schuessler@physics.tamu.edu*

We use two Er^+ fiber lasers with slightly different repetition rates to perform a modern type of Fourier transform spectroscopy without moving parts [1]. The measurements are done in real time and take less than 100μs to record an interferogram. We work with two femtosecond Er^+fiber lasers with somewhat different spectral outputs and employ spectral filtering based on a grating setup to select the common spectral region of interest from the two lasers, thereby increasing the signal to noise ratio. The interferogram is taken with a 20 cm long gas cell, containing a mixture of acetylene and air at atmospheric pressure, and is fast-Fourier-transformed to obtain the spectrum. Dual comb spectroscopy has the multiplex advantages over other comb spectroscopies [2]; it requires only a single fast photodiode (and not a CCD array) and enables acquiring spectra in real time. We acknowledge Qatar Foundation, NPRP grant 09 - 585 - 1 – 087 and the NSF grant No. 1058510.

References

[1] B. Bernhardt, A. Ozawa, P. Jacquet, M. Jacqey, Y. Kobayashi, Th. Udem, R. Holzwarth, G. Guelachvili, T. W. Hänsch and N. Picque, “Cavity-enhanced dual-comb spectroscopy”, Nature Photonics, **4**, 55-57 (2010).
[2] S. A. Diddams, L. Hollberg and V. Mbele, “Molecular fingerprinting with the resolved modes of a femtosecond laser frequency comb”, Nature **445**, 627 (2007).

Theoretical and experimental study of polarization self-rotation for Doppler-broadened rubidium atoms

Eun Hyun Cha, Taek Jeong, and Heung-Ryoul Noh*

Department of Physics, Chonnam National University, Gwangju 500-757, Korea
**hrnoh@chonnam.ac.kr*

We present a theoretical and experimental study of polarization self-rotation of an elliptically polarized light for a Doppler-broadened rubidium atomic cell. The accurate density matrix equations are solved numerically as a function of velocity and elapsed time. Then, the density matrix elements are averaged over atomic transit times and a Maxwell-Boltzmann velocity distribution. We calculate the rotation angle as a function of detuning for various laser intensities and polarizations, and compare the calculated results with experimental results.

Mo-040 Spectroscopy

Observation of enhanced transparency by using coherent population trapping than typical EIT system in the Rb cell

Seung Jin Kim, Hoon Yu, Ye Lin Moon, and Jung Bog Kim

Physics Education, Korea National University of Education, Chung-Buk, Korea republic

We observed high contrast transparency signal in the Rb cell with the buffer gas, 50 torr Ne. We used phase matched two co-propagating lasers (CPT laser) which have linearly orthogonal polarization to make CPT state. And the two lasers which have 6.8 GHz frequency difference corresponds hyperfine splitting of ^{87}Rb make λ-type configuration. Another weak laser which is co-propagating with CPT lasers makes λ-type configuration with a CPT laser and I-type configuration with another CPT laser, simultaneously. We observed three times enhanced transparency signal with three lasers than typical λ-type EIT (electromagnetically induced transparency) signal. We can also observe that the transparency signal has more slow decay shape near resonant region due to more decay channels.

Nonlinearly optical generation of atomic dispersive lineshape to laser frequency stabilization

W. Soares Martins, T. Passerat de Silans*, M. Oriá, and M. Chevrollier

Laboratório de Espectroscopia Ótica, DF-CCEN, Cx. Postal 5086 - Universidade Federal da Paraíba, 58051 - 900 João Pessoa - PB, Brazil
**thierry@otica.ufpb.br*

Avoiding laser frequency drifts is a key issue in many atomic physics experiments. Techniques usually involve either the generation of dispersive atomic lineshapes through frequency modulation of absorptive lines or using differential magnetic shifts of Zeeman sub-levels. Here we describe a simple and robust technique to lock the laser frequency using nonlinear properties of an atomic vapor to produce the dispersive signal [1]. The atomic vapor behaves like a Kerr medium exhibiting self-focusing/-defocusing behavior depending on which side of the resonance the laser frequency is, thus modifying the beam power transmitted through an aperture after the vapor cell. Scanning the frequency across resonance thus results in a dispersive lineshape that can be used as an error signal to lock the laser frequency. This technique exhibits performance similar to usual ones with the advantage of not needing modulation or the use of magnetic fields to be performed.

Reference

[1] F. Queiroga, W. Soares Martins, V. Mestre, I. Vidal, T. Passerat de Silans, M. Oriá and M. Chevrollier, "Laser stabilization to an atomic transition using an optically generated dispersive lineshape", Applied Phys. B: Laser and Optics, doi: 10.1007/s00340-012-4981-.

Singlet-state spectroscopy of the negatively charged nitrogen-vacancy center in diamond

Pauli Kehayias[1,*], Damon English[1], Ran Fischer[2], Andrey Jarmola[1], Kasper Jensen[1], Philip Hemmer[3], Neil Manson[4], and Dmitry Budker[1,5]

1. Department of Physics, University of California, Berkeley, CA 94720, USA
2. Department of Physics, Technion - Israel Institute of Technology, Haifa 32000, Israel
3. Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA
4. Laser Physics Center, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia
5. Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
**pkehayias@berkeley.edu*

The nitrogen-vacancy (NV) color center in diamond consists of a substitutional nitrogen atom in the diamond lattice adjacent to a missing carbon atom (a vacancy). The ground state of the negatively charged NV^- center can be optically spin-polarized and has a long transverse spin relaxation time, which makes it useful for applications such as electric and magnetic field sensing, sub-diffraction-limited imaging, and quantum information. Despite the recent interest in developing these applications, our understanding of the NV^- basic properties is incomplete. Theoretical models disagree on the details of the NV^- energy level structure and predict additional energy states that have not been observed. We have performed broadband absorption spectroscopy out of the metastable ^1E NV^- state in search of previously unobserved states and to study the 1042 nm singlet-singlet phonon sideband. Our findings provide insight on how NV^- singlet states are coupled to phonons and shed light on the energy level structure and optical pumping mechanism.

Photoionization microscopy

Aneta Smolkowska[1,*], Arnaud Rouzée[2], Franck Lépine[3], and Marc Vrakking[1,2]

1. FOM-Institute AMOLF, Science Park 104, 1098 XG Amsterdam, The Netherlands
2. Max-Born-Institut, Max-Born Straße 2A, D-12489 Berlin, Germany
3. Université Lyon 1; CNRS; LASIM, UMR 5579, 43 bvd. du 11 novembre 1918, F-69622 Villeurbanne, France
**smolkowska@amolf.nl*

The principle of photoionization microscopy has been known since the early 80's [1]. In theory it should allow for direct observation one of the most elusive quantum objects - the wave function. Nearly three decades later, with the emergency of the velocity map imaging technique [2], we present an experimental proof of this statement. In our experiment atomic hydrogen is photoexcited into high lying Stark states. The presence of a dc electric field ensures lowering of the potential barrier and leads to autoionization. The ionized electrons are projected on a detector, where they create interference rings due to the existence of different trajectories to the detector. The number of dark fringes equals the parabolic quantum number n_1: the number of nodes of the electronic wave function along the ξ coordinate. By counting these minima we can immediately identify the Stark states. Our experimental findings agree with quantum calculations based on wavepacket propagation.

References
[1] V. D. Kondratovich and V. N. Ostrovsky, J. Phys. B **17,** 1981 (1984).
[2] A. T. J. B. Eppink and D. H. Parker, Rev. Sci. Instrum. 68, 3477 (1997).

Photon recoil heating spectroscopy of metal ions

Piet O. Schmidt[1,2,*], Yong Wan[1,3], Florian Gebert[1], and Börge Hemmerling[1,4]

1. QUEST Institute, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2. Institut für Quantenoptik, Leibniz Universität Hannover, Germany
3. Braunschweig International Graduate School of Metrology, TU Braunschweig, Germany
4. Present address: Physics Department, Harvard University, Cambridge (MA), USA
**Piet.Schmidt@quantummetrology.de*

Many atoms and molecules with interesting spectroscopic properties can not be laser cooled owing to their complex internal level structure. We present a universal spectroscopy system based on sympathetic cooling of a spectroscopy ion through a co-trapped logic ion which is laser cooled [1]. Spectroscopy is performed by monitoring the effect of photon recoil on the motional state of the two-ion crystal. Starting from the motional ground state, scattering of photons near the resonance of a spectroscopy transition leads to photon recoil heating which can be detected efficiently on the logic ion [2]. This allows us to detect the scattering of only 60 photons using a Ca^+ spectroscopy and Mg^+ logic ion. The use of non-classical motional states to enhance the sensitivity will be discussed. The setup is versatile and will allow performing precision spectroscopy of other metal ions relevant to the search for a possible variation of the fine-structure constant using quasar absorption spectroscopy.

References
[1] B. Hemmerling, F. Gebert, Y. Wan, D. Nigg, I. V. Sherstov, and P. O. Schmidt, Appl. Phys. B **104**, 583–590 (2011).
[2] B. Hemmerling, F. Gebert, Y. Wan, and P. O. Schmidt, New J. Phys. **14**, 023043 (2012).

Experimental techniques for studying two-dimensional quantum turbulence in highly oblate Bose-Einstein condensates

Kali Wilson*, E. Carlo Samson, Zachary Newman, and Brian P. Anderson

College of Optical Sciences, University of Arizona, Tucson, Arizona, USA
**kwilson@optics.arizona.edu*

We have developed a collection of techniques for generating large disordered distributions of quantized vortices in highly oblate Bose-Einstein condensates (BECs) for studies of two-dimensional quantum turbulence. In our experimental approach, we generateturbulent states by exciting the condensate either through modulating the trapping magnetic field, or through stirring or swiping the BEC with a blue-detuned laser beam. Additionally, we are developing methods for building up vortex distributions core bycore with control over winding number and vortex positions. These vortex manipulation techniques will allow us to study the vortex dynamics and interactions that are involved in two-dimensional quantum turbulence.

Supported by US NSF and US DOE SCGF.

Beliaev theory of spinor Bose-Einstein condensates

Nguyen Thanh Phuc[1,*], Yuki Kawaguchi[1], and Masahito Ueda[1,2]

1. Department of Physics, University of Tokyo, Japan
2. ERATO Macroscopic Quantum Control Project, Japan
**thanhphuc_85@cat.phys.s.u-tokyo.ac.jp*

By generalizing the Green's function approach proposed by Beliaev [1, 2], we investigate the effect of quantum depletion on the energy spectra of elementary excitations in an F = 1 spinor Bose-Einstein condensate, in particular, of ^{87}Rb atoms in an external magnetic field. We find that quantum depletion increases the effective mass of magnons in the spin-wave excitations with quadratic dispersion relations. The enhancement factor turns out to be the same for both ferromagnetic and polar phases, and also independent of the magnitude of the external magnetic field. The lifetime of these magnons in a ^{87}Rb spinor BEC is shown to be much longer than that of phonons. We propose an experimental setup to measure the effective mass of these magnons in a spinor Bose gas by exploiting the effect of a nonlinear dispersion relation on the spatial expansion of a wave packet of transverse magnetization. This type of measurement has practical applications, for example, in precision magnetometry.

References

[1] S. T. Beliaev, Soviet Physics JETP 7 (1958) 299.
[2] S. T. Beliaev, Soviet Physics JETP 7 (1958) 289.

Trap loss of ultracold metastable helium: non-exponential one-body loss and magnetic-field-dependent two- and three-body loss

Steven Knoop*, Joe Borbely, Rob van Rooij, and Wim Vassen

LaserLaB, VU University Amsterdam, The Netherlands
**s.knoop@vu.nl*

We have experimentally studied the decay of a BEC of metastable ^{4}He atoms in an optical dipole trap, for atoms in the $m = +1$ and $m = -1$ magnetic substates and up to a magnetic field of 450 G [1]. Our measurements confirm long-standing calculations of the two-body loss rate coefficient that show a strong increase above 50 G. We have obtained a three-body loss rate coefficient of $6.5(0.4)_{stat}(0.6)_{sys} \times 10^{-27}$ cm^{6}s^{-1}, which is interesting in the context of universal few-body theory.

In the regime where two- and three-body losses can be neglected, the total number of atoms decays exponentially with time constant τ. However, the thermal cloud decays exponentially with time constant $\frac{4}{3}\tau$ and the condensate decays much faster, and non-exponentially [2]. We have observed this behavior [3], which should be present for all BECs in thermal equilibrium with a considerable thermal fraction.

References

[1] J. S. Borbely, R. van Rooij, S. Knoop, and W. Vassen, *Magnetic-field-dependent trap loss of ultracold metastable helium*, Phys. Rev. A **85**, 022706 (2012).
[2] P. Ziń, A. Dragan, S. Charzyński, N. Herschbach, P. Tol, W. Hogervorst, and W. Vassen, *The effect of atomic transfer on the decay of a Bose-Einstein condensate*, J. Phys. B **36**, L149 (2003).
[3] S. Knoop, J. S. Borbely, R. van Rooij, and W. Vassen, *Non-exponential one-body loss in a Bose-Einstein condensate*, Phys. Rev. A **85**, 025602 (2012).

Quantum criticality of spin-1 bosons in a 1D harmonic trap

C. C. N. Kuhn[1,2,*], X. W. Guan[2], A. Foerster[1], and M. T. Batchelor[2,3]

1. Instituto de Fisica da UFRGS, Av. Bento Goncalves 9500, Porto Alegre, RS, Brazil
2. Department of Theoretical Physics, Research School of Physics and Engineering, Australian National University
3. Mathematical Sciences Institute, Australian National University, Canberra ACT 0200, Australia
**carlos.kuhn@ufrgs.br*

We investigate universal thermodynamics and quantum criticality of spin-1 bosons with strongly repulsive density-density and antiferromagnetic spin-exchange interactions in a one-dimensional harmonic trap. From the equation of state, we find that a partially-polarized core is surrounded by two wings composed of either spin-singlet pairs or a fully spin-aligned Tonks-Girardeau gas depending on the polarization. We describe how the scaling behaviour of density profiles can reveal the universal nature of quantum criticality and map out the quantum phase diagram. We further show that at quantum criticality the dynamical critical exponent $z = 2$ and correlation length exponent. $\nu = 1/2$. This reveals a subtle resemblance to the physics of the spin-1/2 attractive Fermi gas.

References

[1] C. C. N. Kuhn, X. W. Guan, A. Foerster and M. T. Batchelor, arXiv:1111.2375v1 [cond-mat.quant-gas] 2012 - submeted to PRL.
[2] C. C. N. Kuhn, X. W. Guan, A. Foerster and M. T. Batchelor, arXiv:1201.6456v1 [cond-mat.quant-gas] - submeted to PRA.

Measurement of momentum distribution of one dimensional quasiBEC using focusing techniques

Thibaut Jacqmin[1], Bess Fang[1], Tarik Berrada[2], Tommaso Roscilde[3], and Isabelle Bouchoule[1]

1. Laboratoire Charles Fabry, CNRS UMR 8501, Institut d'Optique, 91127 Palaiseau Cedex, France
2. Vienna Center for Quantum Science and Technology, Atominstitut,
TU Wien, Stadionallee 2, 1020 Vienna, Austria
3. Laboratoire de Physique, CNRS UMR 5672, École normale supérieure de Lyon,
Université de Lyon, 46 Allée d'Italie, Lyon, F-69364, France
**bess.fang@institutoptique.fr*

We measure the momentum distribution of one-dimensional quasi-BEC using focusing techniques. By varing the temperature and density, the crossover from ideal Bose gas to quasi-condensate is probed. We model our data using a classical field theory [1] and obtain a temperature similar to that extracted from *in situ* density fluctuation measurements [2]. We also compare our results with Quantum Monte Carlo calculations.

References
[1] Y. Castin *et al.*, *Coherence properties of a continuous atom laser*, J. of Mod. Optics **47**, 2671 (2000).
[2] J. Estève *et al.*, *Observations of density fluctuations in an elongated Bose gas: ideal gas and quasi-condensate regimes*, Phys. Rev. Lett. **96**, 130403 (2006).

Feshbach spectroscopy of an ultracold ^{85}Rb-^{133}Cs mixture

H.-W. Cho[1], D. L. Jenkin[1], M. Köppinger[1], D. J. McCarron[1], C. L. Blackley[2], C. R. Le Sueur[2], J. M. Hutson[2], and S. L. Cornish[1,*]

1. Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
2. Department of Chemistry, Durham University, South Road, Durham DH1 3LE, UK
**s.l.cornish@durham.ac.uk*

Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment. The anisotropic, long range dipole-dipole interactions between such molecules offers many potential applications, including novel schemes for quantum information processing and simulation. Our goal is to create ultracold ground-state RbCs molecules using magneto-association on a Feshbach resonance followed by optical transfer to the rovibronic ground state. The pre-requisite to this approach is the attainment of a high phase space density atomic mixture and the identification of suitable interspecies Feshbach resonances. Here we present the latest results from our experiment, including the realisation of a quantum degenerate mixture of ^{87}Rband ^{133}Cs [1] and a detailed study of the Feshbach spectrum of an ultracold ^{85}Rb–^{133}Cs mixture.

Reference
[1] D. J. McCarron, H. W. Cho, D. L. Jenkin, M. P. Koeppinger and S. L. Cornish, *Dual-species Bose-Einstein condensate of 87Rb and 133Cs*, Phys. Rev. A 84 011603 (2011).

Quantum tri-criticality and phase transitions in spin-orbit coupled Bose-Einstein condensates

Yun Li*, Lev P. Pitaevskii, and Sandro Stringari

Dipartimento di Fisica, Università di Trento and INO-CNR BEC Center, I-38123 Povo, Italy
**li@science.unitn.it*

We consider a spin-orbit coupled configuration of spin-1/2 interacting bosons with equal Rashba and Dresselhaus couplings. The phase diagram of the system at $T = 0$ is discussed with special emphasis to the role of the interaction, treated in the mean-field approximation. For a critical value of the density and of the Raman coupling we predict the occurrence of a characteristic tri-critical point separating the spin mixed, the phase separated and the zero momentum states of the Bose gas. The corresponding quantum phases are investigated analyzing the momentum distribution, the longitudinal and transverse spin-polarization and the emergence of density fringes. The effect of harmonic trapping as well as the role of the breaking of spin symmetry in the interaction Hamiltonian are also discussed.

Reference

[1] Y. Li, L. P. Pitaevskii, and S. Stringari, *Quantum tri-criticality and phase transitions in spin-orbit coupled Bose-Einstein condensates*, arXiv:1202.303.

Melting of fractional vortex lattice in a rotating spin-1 antiferromagnetic Bose-Einstein condensate at finite temperatures

S.-W. Su[1], I.-K. Liu[2], P. B. Blakie[3], A. S. Bradley[3], and S.-C. Gou[2]

1. Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
2. Department of Physics, National Changhua University of Education, Changhua 50058, Taiwan
3. Department of Physics, University of Otago, Dunedin 9016, New Zealand

The stability of the half-quantized vortex lattice in the rotating spin-1 antiferromagnetic Bose- Einstein condensate [1] is studied at finite temperatures. By solving the stochastic projected Gross- Pitaevskii equation [2], we study how the lattice structures in both superfluid densities and spin texture are distorted and melted at higher temperatures. We find that the half-quantized vortex lattice and the domain wall of the spin texture are vulnerable to the thermal fluctuations. In the typical experiments of spinor BEC, the lowest temperature attainable is about 50 nK [3] which is much higher than that of a scalar BEC. Our investigations simulate the equilibrium configuration of the half-quantized vortex lattice in a rotating spin-1 BEC when thermal fluctuations are important.

References

[1] S.-W. Su, C.-H. Hsueh, I.-K. Kiu, T.-L. Horng, Y.-C. Tsai, S.-C. Gou and W. M. Liu, *Spontaneous crystallization of skyrmions and fractional vortices in fast-rotating and rapidly quenched spin-1 Bose-Einstein condensates*, Phys. Rev. A**84**, 023601 (2011).
[2] S. J. Rooney, P. B. Blakie, B. P. Anderson and A. S. Bradley, *Suppression of Kelvon-induced decay of quantized vortices in oblate Bose-Einstein condensate*, Phys. Rev. A **84**, 023637 (2011).
[3] M. Vengalattore, S. R. Leslie, J. Guzman, and D. M. Stamper-Kurn *Spontaneously Modulated Spin Textures in a Dipolar Spinor Bose-Einstein Condensate*, Phys. Rev. A **100**, 170403 (2008).

Bose-Einstein condensate in a highly anisotropic dressed quadrupole trap

Karina Merloti*, Romain Dubessy, Laurent Longchambon, Paul-Eric Pottie,
Aurélien Perrin, Vincent Lorent, and Hélène Perrin

Laboratoire de physique des lasers, CNRS and Université Paris 13
99 avenue Jean-Baptiste Clément, 93430, Villetaneuse, France
**karina.merloti@univ-paris13.fr*

We demonstrate the trapping of a ^{87}Rb Bose-Einstein condensate in a very anisotropic radio-frequency (RF) dressed quadrupole trap. The condensate is first produced in a magnetic quadrupole trap plugged in its center by a blue detuned laser, carefully optimized to overcome Majorana losses [1]. Once condensed, the atoms are transferred to the dressed trap by sweeping the RF frequency and removing slowly the plug laser. In the dressed trap, the RF coupling is precisely determined by spectroscopy and the lifetime of the dressed atoms reaches several minutes. The oscillation frequencies are measured for different values of the RF field and magnetic gradient, indicating the achievement of a highly anisotropic trap. For the maximum value of the magnetic gradient, we reach the two-dimensional regime for the degenerate gas.

Our results represent an important step towards the realization of a ring-shape trap [2] where we will investigate the connection between superfluidity and Bose-Einstein condensation in 2D and 3D.

References

[1] R. Dubessy *et al.*, *Rubidium-87 Bose-Einstein condensate in an optically plugged quadrupole trap*, Phys. Rev. A **85**, 013643 (2012).
[2] O. Morizot *et al.*, *Ring trap for ultracold atoms*, Phys. Rev. A **74**, 023617 (2006).

Quantum and thermal transitions out of the pair-supersolid phase of two-species bosons in lattice

Chia-Min Chung, Shiang Fang, and Pochung Chen*

Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
**pcchen@phys.nthu.edu.tw*

We investigate two-species bosons in a two-dimensional square lattice by quantum Monte Carlo method. We show that the inter-species attraction and nearest-neighbor intra-species repulsion results in the pair-supersolid phase, where a diagonal solid order coexists with an off-diagonal pair-superfluid order. The quantum and thermal transitions out of the pair-supersolid phase are characterized. It is found that there is a direct first order transition from the pair-supersolid phase to the double-superfluid phase without an intermediate region. Furthermore, the melting of the pair-supersolid occurs in two steps. Upon heating, first the pair-superfluid is destroyed via a Kosterlitz-Thouless transition then the solid order melts via an Ising transition.

Reference

[1] Chia-Min Chung, Shiang Fang, and Pochung Chen, *Quantum and Thermal Transitions Out of the Pair-Supersolid Phase of Two-Species Bosons in Lattice*, arXiv:1203.5629.

Bose-Einstein condensation in quantum crystals: the quest of supersolidity

Riccardo Rota[1,*] and Jordi Boronat[2]

1. Dipartimento di Fisica and CNR-INO BEC Center, Università degli Studi di Trento, via Sommarive 14, 38123 Trento, Italy
2. Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, Campus Nord B4-B5, 08034 Barcelona, Spain
**rota@science.unitn.it*

The experimental observation of superfluidity effects in solid ^{4}He at low temperature [1] suggests the existence of a *supersolid* state of matter, i.e. a crystalline phase performing Bose-Einstein condensation (BEC). Although the first conjectures on supersolidity appeared some decades ago, a reliable microscopic model of this phenomenon is still lacking, since it is hard to describe the competing effects of localization, due to the crystalline order, and delocalization, due to the zero-point motion, which characterize the atoms in quantum solids. In this work, we present a microscopic approach to the solid phase of ^{4}He, based on Path Integral Monte Carlo simulations. In particular, we compute the one-body density matrix $\rho_1(r)$ of ^{4}He crystals at different temperatures, in order to study the BEC properties of these systems: we find that perfect crystals do not support BEC at any temperature [2] and that crystals presenting vacancies below a certain temperature become supersolid [3].

References

[1] E. Kim and M. H. W. Chan, Nature, **427**, 225 (2004).
[2] R. Rota and J. Boronat, J. Low. Temp. Phys., **162**, 146 (2011).
[3] R. Rota and J. Boronat, Phys. Rev. Lett., **108**, 045308 (2012).

Quantum Monte Carlo study of a resonant Bose-Fermi mixture

Gianluca Bertaina[1,*], Elisa Fratini[2], Stefano Giorgini[3], Pierbiagio Pieri[2], and Vincenzo Savona[1]

1. Institute of Theoretical Physics, Ecole Polytechnique Fédérale de Lausanne EPFL, CH-1015 Lausanne, Switzerland
2. Sezione di Fisica, Scuola di Scienze e Tecnologie, Università di Camerino and CNISM, I-62032 Camerino, Italy
3. INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy
**gianluca.bertaina@epfl.ch*

We study resonant Bose-Fermi mixtures at zero temperature, with different relative concentrations of the bosons. We use for the first time a Quantum Monte Carlo method with Fixed-Node approximation, to explore the system from the weak to the strong coupling limit. A repulsive interaction among bosons is introduced to provide stability to the bosonic component. Beyond the unitarity limit, the resonant attractive interaction supports a bound fermionic dimer. At the many-body level, increasing the boson-fermion coupling the system undergoes a quantum phase transition from a state with condensed bosons immersed in a Fermi sea, to a normal Fermi-Fermi mixture of the composite fermions and the bare fermions in excess. We obtain the equation of state and we characterize the momentum distributions both in the weakly and in the strongly interacting limits. We compare QuantumMonte Carlo results to T-matrix calculations, finding interesting signatures of the different many-body ground states.

Non-Abelian spin singlet states of bosons in artificial gauge fields

Tobias Grass[1,*], Bruno Juliá-Díaz[1], Nuria Barberán[2], and Maciej Lewenstein[1,3]

1. ICFO-Institut de Ciències Fotòniques, Parc Mediterrani de la Tecnologia, Barcelona, Spain
2. Dept. ECM, Facultat de Física, U. Barcelona, Barcelona, Spain
3. ICREA-Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain
**tobias.grass@icfo.es*

Using exact diagonalization we study strongly correlated phases of a two-component Bose gas in an artificial gauge field. The atoms are confined in two dimensions and interact via a two-body contact. We show that for SU(2) symmetric interactions and Abelian gauge fields the correlated nature of the system energetically favors spin singlets. Incompressible phases are formed at fillings $\nu = 2k/3$, for which, in close analogy to the Read-Rezayi (RR) series in spin-polarized systems, a series of non-Abelian spin singlet (NASS) states is known, being the exact zero-energy eigenstates of a $(k + 1)$-body contact interaction. Explicit calculations reveal the relevance of these states also for our system with a realistic two-body interaction. Subjecting the atoms to non-Abelian gauge fields, it becomes possible to switch between RR-like and NASS-like states by varying the non-Abelian gauge field strength.

Confined *p*-band Bose-Einstein condensates

Fernanda Pinheiro[1,2,*], Jani-Petri Martikainen[2,3], and Jonas Larson[3,4]

1. Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden
2. NORDITA, SE-10691 Stockholm, Sweden
3. Aalto University, P.O. Box 1510, FI-00076 Aalto, Finland
4. Institut für Theoretische Physik, Universität zu Köln, DE-50937 Köln, Germany
**fep@fysik.su.se*

We study bosonic atoms on the p band of a two-dimensional optical square lattice in the presence of a confining trapping potential. Using a mean-field approach, we show how the anisotropic tunneling for p-band particles affects the cloud of condensed atoms by characterizing the ground-state density and the coherence properties of the atomic states both between sites and atomic flavors. In contrast to the usual results based on the local-density approximation, the atomic density can become anisotropic. This anisotropic effect is especially pronounced in the limit of weak atom-atom interactions and of weak lattice amplitudes, i.e., when the properties of the ground state are mainly driven by the kinetic energies. We also investigate how the trap influences known properties of the non-trapped case. In particular, we focus on the behavior of the antiferromagnetic vortex-antivortex order, which for the confined system is shown to disappear at the edges of the condensed cloud.

Reference

[1] Fernanda Pinheiro, Jani-Petri Martikainen and Jonas Larson *Confined p-band Bose-Einstein condensates*, Phys. Rev. A **85**, 033638 (2012).

Negative magneto-resistance in disordered ultra-cold atomic gases

Joseph Towers[1] and David A. W. Hutchinson[1,2,*]

1. Department of Physics, University of Otago, Dunedin, New Zealand
2. Centre for Quantum Technologies, National University of Singapore, Singapore 117543
**david.hutchinson@otago.ac.nz*

Anderson Localization[1] was first investigated in the context of electrons in solids. One success of Anderson's theory of weak localisation was in explaining the puzzle of negative magneto-resistance[2] – as early as the 1940s it had been observed that electron diffusion rates in some materials can increase with the application of a magnetic field. This is because Anderson Localization is an interference phenomenon and breaking time reversal symmetry through the application of an external magnetic field inhibits that interference. Anderson Localization has already been demonstrated in one dimensional ultra-cold atomic gases[3]. We present a theoretical demonstration of weak localisation in a two-dimensional Bose condensed gas. We then demonstrate that a synthetic magnetic field can be imposed on the gas using the scheme of Spielman[4]. We show that this can lead to both positive and negative magneto-resistance in the gas and provide an in-depth analysis of the resulting phases.

References

[1] P. W. Anderson, Phys. Rev. **109**, 1492 (1958).
[2] See, for example, in P. A. Grüberg, Rev. Mod. Phys. **80**, 1531 (2008) for an historical discussion of magnetoresistance in general.
[3] J. Billy *et al.*, Nature **453**, 891 (2008); G. Roati *et al.*, Nature **453**, 895 (2008).
[4] Y.-J. Line *et al.*, Nature **462**, 628 (2009).

Faraday imaging of Bose-Einstein condensates

Miroslav Gajdacz, Poul Pedersen, Troels Mørch, Jacob Sherson, and Jan Arlt*

Institut for Fysik og Astronomi, Aarhus Universitet, Ny Munkegade 120, DK-8000 Århus C
**arlt@phys.au.dk*

Faraday rotation has a long and fruitful history in atomic physics and quantum optics. It describes the rotation of the polarization of a light beam as it passes through a medium. The effect has been employed very successfully in atomic gases at room temperature and in laser cooled atomic ensembles, resulting in e.g. squeezing and entanglement of atomic spins and for quantum information protocols.

Here we demonstrate the use of Faraday rotation to non-destructively image ultra cold atomic clouds and Bose-Einstein condensates. We show that dark ground Faraday imaging allows us to take many images of a single ultra cold cloud and present a detailed analysis of the destructiveness. This ability allows us to monitor e.g. the condensation process or the inherent oscillation of these atomic samples in a single experimental realization.

Our experiments are performed with ultra cold ^{87}Rb samples using light at a blue detuning of 0-1.5 GHz from the D2 transition. We present the laser system to generate the off-resonant light and show that we have obtained good quantitative agreement between the observed and predicted Faraday rotation both in room temperature and ultra cold samples.

In the future we will extend this technique to high resolution imaging of atomic samples in optical lattices and to multi component quantum gases. This will allow for probing and control of these systems beyond the quantum noise level.

Ab initio stochastic description of 5 fluctuating quasicondensate experiments

Nick P. Proukakis*, Donatello Gallucci, and Stuart P. Cockburn

Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
**nikolaos.proukakis@ncl.ac.uk*

The proposed modified form of the stochastic Gross-Pitaevskii equation [1] is demonstrated to be an excellent tool for *ab initio* studies of (quasi-)one-dimensional weakly-interacting Bose gases (supplemented here by self-consistent treatment of radially-excited thermal modes). In the regime $\mu < \hbar\omega_\perp$ we show [1] that this model accurately reproduces densities and density fluctuations in atom chip experiments of Bouchoule [2, 3] and van Druten [4]; in the regime $\mu <$ few $\hbar\omega_\perp$ we also demonstrate excellent reconstruction of earlier quasi-one-dimensional phase fluctuation experiments in the group of Alain Aspect (PRL 2003; EPJD 2005). We acknowledge funding from EPSRC (EP/F055935/1).

References

[1] S. P. Cockburn, D. Gallucci and N. P. Proukakis, *Quantitative study of quasi-one-dimensional Bose gas experiments via the stochastic Gross-Pitaevskii equation*, Phys. Rev. A **84**, 023613 (2011).
[2] J.-B. Trebbia *et al.*, *Experimental Evidence for the Breakdown of a Hartree-Fock Approach in a Weakly Interacting Bose Gas*, Phys. Rev. Lett. **97**, 250403 (2006).
[3] J. Armijo *et al.*, *Probing Three-Body Correlations in a Quantum Gas Using the Measurement of the Third Moment of Density Fluctuations*, Phys. Rev. Lett. **105**, 230402 (2010).
[4] A. H. van Amerongen, J. J. P. van Es, P. Wicke, K. Kheruntsyan and N. J. van Druten, *Yang-Yang Thermodynamics on an Atom Chip*, Phys. Rev. Lett. **100**, 090402 (2008).

Bose gases Mo-062

Pre-thermalization in an isolated many-body quantum system

Remi Geiger[1,*], Tim Langen[1], Michael Gring[1], Maximilian Kuhnert[1], Bernhard Rauer[1], Igor Mazets[1], Takuya Kitagawa[2], Eugene Demler[2], David A. Smith[1] and Jörg Schmiedmayer[1]

1. Vienna Center for Quantum Science and Technology,
Atominstitut, TU Wien, Stadionallee 2, 1020 Wien, Austria
2. Harvard-MIT Center for Ultracold Atoms, Department of Physics,
Harvard University, Cambridge, Massachusetts 02138, USA
**rgeiger@ati.ac.at*

Understanding non-equilibrium processes in many-body quantum systems is an important open problem in physics. We study the relaxation dynamics of a coherently split one-dimensional Bose gas on an atom chip by performing time-resolved measurements of the probability distribution function of matter-wave interferences. After (fast) splitting, the system follows a rapid evolution before reaching a quasi-steady state. This state is characterized by an effective temperature for the condensates relative phase degrees of freedom, which we observe to be independent on the initial temperature of the gas (before splitting) and determined by the atom number fluctuations corresponding to the splitting process. We do not observe the onset of thermalization on the time-scale achievable by our experiment, and associate this relaxation dynamics with the phenomenon of pre-thermalization. We will report our new results for the dynamics of a system with tunnel coupling bewteen the two parts of the split condensate.

Thermodynamic analysis of a trapped BEC using global variables

P. C. M. Castilho[1,*], F. J. Poveda-Cuevas[1], P. Dyke[2], R. G. Hulet[2], S. R. Muniz[1], and V. S. Bagnato[1]

1. Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brasil
2. Department of Physics and Astronomy and Rice Quantum Institute, Rice University, Houston, Texas, USA
**patricia.cmcastilho@gmail.com*

Using the concept of global variables to describe the thermodynamic properties of a trapped Bose-Einstein Condensate [1] we have performed two classes of experiments. In a first experiment, a BEC of ^{7}Li held in an optical trap in an almost 1D regime, was employed to explore the contributions of the condensate and the thermal clouds to the overall pressure of the system. Different scattering lengths were considered and we could demonstrate the dominance of the condensate contribution for $T \ll T_c$. In a second experiment, we have used a BEC of ^{87}Rb trapped in a hybrid trap, composed by the combination of a magnetic and an optical trap. In this type of trap it is possible to vary the geometry of the system, going from an almost spherical BEC to a very elongated cigar-shaped one, providing the possibility to study different regimes. One of the studies in progress is the investigation of the thermodynamic transformations of the condensate as well as the determination of the order of the BEC transition for an inhomogeneous trapped gas.

Reference
[1] Romero-Rochin, V.; Shiozaki, R. F.; Caracanhas M.; Henn, E.; Magalhães, K. M. F.; Roati, G. and Bagnato, V. S., "Observation of a Bose-Einstein condensation in an atomic trap in terms of macroscopic thermodynamic parameters", Physical Review A, v. 85, p. 023632 (2012).

A 1D Bose gas in a box trap on an atom chip

Quentin Beaufils*, Wojciech Lewoczko-Adamczyk, Steven Lepoutre, and N. J. van Druten

Van der Waals-Zeeman Institute, University of Amsterdam, Science Park 904,
1098 XH Amsterdam, The Netherlands
**Q.A.BeaufilsdelaRancheraye@uva.nl*

Atom chips give promising access to tailored axial potentials for one-dimensional (1D) gases by employing specifically designed wire patterns. The magnetic trapping potential of our chip features a strong harmonic confinement in the radial direction combined with a box-like confinement along the axial direction [1]. The ideal Bose gas behaves rather differently in a box when compared to a harmonic trap [2]. Furthermore, homogeneity of the atomic density along the 1D axis allows a closer comparison to exact theoretical treatments, without the need for the local-density approximation. We characterise the loading of 1D Bose gases near quantum degeneracy in the box trap and the influence of potential roughness on the density distribution. The prospects of reaching the strongly interacting regime by reducing the density are investigated.

References
[1] J. J. P. van Es *et al.*, *Box traps on an atom chip for one-dimensional quantum gases*, J. Phys. B. **43**, 155002 (2010).
[2] S. R. de Groot, G. J. Hooyman, and C. A. ten Seldam, Proc. R. Soc. London Ser. A 203, 266 (1950).

Vortex dipole in a dipolar Bose Einstein condensate

Züleyha Öztaş* and Cem Yüce

Anadolu University, Eskişehir, Turkey
**zdonmez@anadolu.edu.tr*

We studied a single charged quantized vortex dipole in a dipolar Bose Einstein Condensate (BEC) in the Thomas Fermi (TF) limit. We calculated the critical velocity for the formation of a pair of vortices with opposite charge in an oblate dipolar BEC. We made a comparision between the critical velocities of dipolar and nondipolar condensates. The dependence of the critical velocity on the dipolar interaction strength and vortex seperation was discussed. We found that dipolar interactions change the critical velocity of vortex dipole and affect the superfluid properties of BEC.

References

[1] Z. Öztaş, "Vortices in a BEC with dipole-dipole interactions", PhD Dissertation, Anadolu University, Graduate School of Sciences, Eskişehir (2011).
[2] M. Crescimanno, C. G. Koay, R. Peterson and R. Walsworthand, "Analytical estimate of the critical velocity for vortex pair creation in trapped Bose condensates", Phys. Rev. A, 62, 063612, (2000).

A mesoscopic gas of spin 1 bosons

Lingxuan Shao*, David Jacob, Vincent Corre, Jean Dalibard, Fabrice Gerbier, Emmanuel Mimoun, and Luigi de Sarlo

Laboratoire Kastler Brossel, 24 rue Lhomond, 75005 Paris, France
**lingxuan.shao@lkb.ens.fr*

One of the most active topic in the field of ultra cold quantum gases is the study of interacting many-body systems with spin [1,2]. Atoms with arbitrary Zeeman structure can be trapped by far-detuned optical traps. In our group, we construct an all-optical setup in order to study spin 1 condensates in sodium gases. We achieved to reach Bose-Einstein condensation regime by MOT pre-cooling and two-stages evaporative cooling, with about 5000 atoms. We explore the phase diagram with magnetization and magnetic field at low temperature in equilibrium state. Two phases are found, reflecting a competition between the spin-dependent interaction and the quadratic Zeeman energy. The measurements are in quantitative agreement with mean-field theory and single mode approximation. We also notice an abnormal large fluctuation at small magnetization and low magnetic field, which opens future works for us.

References

[1] T.-L. Ho, Phys. Rev. Lett. 81, 742 (1998).
[2] T. Ohmi and T. Machida, J. Phys. Soc. Jpn 67, 1822 (1998).

First and second sound in an ultra-cold Bose gas

A. Groot*, P. C. Bons, and P. van der Straten

Nanophotonics, Debye Institute, Utrecht University, The Netherlands
**A. Groot@uu.nl*

First and second sound are the hallmarks of two-fluid hydrodynamics. These sound modes consist of density and temperature modulations in the non-condensed and condensate fractions of an ultra-cold bosonic gas. There is a coupling between first and second sound, leading to an avoided crossing at a temperature around 0.05 Tc, which has never seen been experimentally. To investigate the dispersion relation of these modes, two approaches are followed. First, a perturbation is made in the potential creating a travelling sound wave[1]. In a second experiment, a standing sound wave is induced by periodically modulating the trapping potential. Using phase-contrast imaging[2] and singular value decomposition, the speed of sound and the dispersion relation are extracted from these experiments.

References

[1] R. Meppelink *et al.* "Sound propagation in a Bose-Einstein condensate at finite temperatures" Phys. Rev. A **80**, 043605 (2009).
[2] R. Meppelink *et al.* "Thermodynamics of Bose-Einstein-condensed clouds using phase-contrast imaging" Phys. Rev. A **81**, 053632 (2010).

Time averaged optical traps with an all optical BEC

L. Humbert, M. Baker*, S. A. Haine, M. W. J. Bromley, M. J. Davis, N. R. Heckenberg, and H. Rubinsztein-Dunlop

School of Mathematics and Physics, University of Queensland, St Lucia, QLD, 4072
**m.baker@physics.uq.edu.au*

We report on our preliminary results of a toroidal trap for BEC of ^{87}Rb using time averaged optical potentials [1]. Our apparatus consists of a crossed dipole trap formed by two focused beams of 1064 nm light overlapping in the horizontal plane. Atoms are initially loaded to a single beam dipole trap from a standard 3D-MOT. Evaporative cooling is first performed in the single beam trap, followed by compression and additional confinement with a second orthogonal beam [2]. We achieve nearly pure condensates of 10^4 atoms in the $F = 1$ ground state. Spin state selection is achieved via application of magnetic gradients during the evaporation. The toroidal trap is formed from a third beam in the vertical direction that is scanned by a 2D AOM, with additional confinement of the atoms by a light sheet.

References

[1] S. K. Schnelle, E. D. van Ooijen, M. J. Davis, N. R. Heckenberg, H. Rubinsztein-Dunlop, "Versatile two-dimensional potentials for ultra-cold atoms", Opt. Express **16** (3), 1405 (2008).
[2] K. J. Arnold, M. D. Barrett, "All-optical BEC in a 1.06 µm dipole trap", Opt. Commun. **284**, 3288 (2011).

Breathing oscillations of a trapped impurity in a Bose gas

T. H. Johnson[1,*], M. Bruderer[2], Y. Cai[3], S. R. Clark[4,1,5], W. Bao[3,6], and D. Jaksch[1,4,5]

1. Clarendon Laboratory, University of Oxford - Parks Road, Oxford OX1 3PU, UK, EU
2. Fachbereich Physik, Universität Konstanz - D-78457 Konstanz, Germany, EU
3. Department of Mathematics, National University of Singapore - 119076, Singapore
4. Centre for Quantum Technologies, National University of Singapore - 3 Science Drive 2, 117543
5. Keble College, University of Oxford - Parks Road, Oxford OX1 3PG, UK, EU
6. Center for Computational Science and Engineering, National University of Singapore - 117543
**t.johnson1@physics.ox.ac.uk*

Motivated by a recent experiment (Catani J. *et al.*, *Phys. Rev. A*, 85 (2012) 023623) we study breathing oscillations in the width of a harmonically trapped impurity interacting with a separately trapped Bose gas. We provide an intuitive physical picture of such dynamics at zero temperature, using a time-dependent variational approach. The amplitudes of breathing oscillations are suppressed by self-trapping, due to interactions with the Bose gas. Further, exciting phonons in the Bose gas leads to damped oscillations and non-Markovian dynamics of the width of the impurity, the degree of which can be engineered through controllable parameters. Our results, supported by simulations, reproduce the main features of the dynamics observed by Catani *et al.* despite the temperature of that experiment. Moreover, we predict novel effects at lower temperatures due to self-trapping and the inhomogeneity of the trapped Bose gas.

Reference

T. H. Johnson *et al.*, *Europhys. Lett.*, 98 (2012) 26001.

Healing-length scale control of a Bose-Einstein condensate's wavefunction

Stuart Szigeti[1], Russell Anderson[2], Lincoln Turner[2], and Joseph Hope[1]

1. The Australian National University, Canberra, Australia
2. Monash University, Melbourne, Australia
**stuart.szigeti@anu.edu.au*

Arbitrary engineering of a Bose-Einstein condensate's (BEC's) quantum state at the healing-length scale has many applications across ultracold atomic science, including atom interferometry [1], quantum simulation and emulation [2,3] and topological quantum computing [4]. However, to date the BEC wavefunction is most commonly manipulated with laser light, which is diffraction limited. Here we present a scheme, based upon radiofrequency (RF) resonance and magnetic field gradients, that can be used to apply arbitrary spatially-dependent phase shifts to the BEC order parameter at the healing-length scale.

References

[1] B. Benton, M. Krygier, J. Heward, M. Edwards and C. W. Charles, Phys. Rev. A, **84**, 043648 (2011).
[2] I. Buluta and F. Nori, Science, **326**, 5949 (2009).
[3] D. Jaksch and P. Zoller, Annals of Physics, **315**, 52–79 (2005).
[4] C. Nayak, S. H. Steven, A. Stern, M. Freedman and S. Das Sarma, Rev. Mod. Phys., **80**, 1083–1159 (2008).

A spin Hall effect in ultracold atoms

M. C. Beeler[1,*], L. J. LeBlanc[1], R. A. Williams[1], K. Jiménez-García[1,2], A. R. Perry[1], and I. B. Spielman[1]

1. Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, U.S.A.
2. Departamento de Física, Centro de Investigación y Estudios Avanzados del Instituto Politécnico Nacional, Mexico
**beeler@nist.gov*

The spin Hall effect is a phenomenom that couples spin current to particle current via spin-orbit coupling. The effect may be used to develop useful devices for spintronics, which may have advantages over corresponding conventional electronic devices. In addition, the spin-Hall effect is intimately related to certain types of topological insulators. Spin-orbit coupling in an ultracold bosonic sample of ^{87}Rb has been demonstrated [1]. We now use this spin-orbit coupling to produce a spin Hall effect in a bosonic sample, the first demonstration of the effect in an ultracold atom system.

Reference

[1] Lin Y. -J., Jimémez-García, K., and Spielman, I. B., *Spin-orbit coupled Bose-Einstein condensates*, Nature **471**, pp. 83-86 (2011).

The roles of the two zero and adjoint modes in the dynamics of dark soliton

J. Takahashi*, Y. Nakamura, and Y. Yamanaka

Department of Elecrtonic and Photonic Systems, Waseda University, Tokyo 169-8555, Japan
**d.junichi.takahashi@gmail.com*

The dark solitons have been observed in BEC experiments. They are stable in 1D, but collapse in higher dimensions [1]. The existence of the zero and adjoint modes is known in the Bogoliubov-de Gennes (BdG) analysis, widely used to study the fluctuation and excitation spectrum in BECs. The zero mode corresponds to the Nambu-Goldstone mode, and the adjoint mode ensures thecompleteness of the set of eigenfunctions. In the case of the single-component system for which a translational symmetry is broken explicitly, there is only one zero mode. The roles of this zero and its adjoint modes are to translate the phase of condensate and to conserve the number of condensate, respectively evortex. We consider the case where the soliton exists in BEC and therefore a translational symmetry is spontaneously broken. Then the BdG equation has two pairs of the zero and adjoint modes, associated with the phase and translational symmetries. We discuss their roles in the dynamics of dark soliton.

References

[1] V. Tikhonenko, J. Christou, B. Luther-Davies, and Y. S. Kivshar, Opt. Lett. **21**,15 (1996).
[2] K. Kobayashi, Y. Nakamura, M. Mine, and Y. Yamanaka, Ann. Phys. **324**, 2359 (2009).

Mode competition in superradiant scattering of matter waves

Xuzong Chen*, Xuguang Yue, Yueyang Zhai, Thibault Vogt, and Xiaoji Zhou

School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, People's Republic of China
**xuzongchen@pku.edu.cn*

The coherent nature of Bose-Einstein condensates has led to new and rapid developments in atom optics and studies on coherent interaction between light and matter waves. Superradiant Rayleigh scattering in a Bose gas released from an optical lattice is analyzed with incident light pumping at the Bragg angle for resonant light diffraction. We show that competition between superradiance scattering into the Bragg mode and into end-fire modes clearly leads to suppression of the latter at even relatively low lattice depths. A quantum light-matter interaction model is proposed for qualitatively explaining this result [1]. Based on this mechanism of amplification of matter waves, we show a method to measure the global coherence function in a Bose gas loaded in a 1D optical lattice with a resolution of one lattice spacing [2].

References
[1] T. Vogt, B. Lu, X. Liu, X. Xu, X. J. Zhou and X. Z. Chen, Phys. Rev. A 83 053603 (2011).
[2] B. Lu, T. Vogt, X. Liu, X. Xu, X. J. Zhou, and X. Z. Chen, Phys. Rev. A 83, 051608(R) (2011).

Nucleation of vortices in a Bose Einstein Condensate

M. W. Ray and D. S. Hall*

Department of Physics, Amherst College, Amherst, MA, USA
**dshall@amherst.edu*

We present experimental studies of the nucleation of small numbers of vortices in a Bose-Einstein Condensate. The vortices are nucleated in a rotating frame during evaporative cooling of the system, and using extraction imaging techniques [1], we produce images of a condensate being formed with vortices. We find that the condensate is created with a set number of vortices determined by the rotation frequency when passing through the BEC transition. After the condensate begins to form, we observe that additional vortices cannot be added to the system unless the rotation drives a collective mode of the condensate. We also observe that when multiple vortices are formed, they do not, in general, apppear in ordered configurations.

Reference
[1] D. V. Freilich et. al. *Real-Time Dynamics of Single Vortex Lines and Vortex Dipoles in a Bose-Einstein Condensate*, Science **329**, 1182 (2010).

Non-equilibrium dynamics of an unstable quantum many-body pendulum

C. S. Gerving, T. M. Hoang, B. J. Land, M. Anquez, C. D. Hamley, and M. S. Chapman

School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0430, USA
**mchapman@gatech.edu*

We measure the non-equilibrium quantum dynamics of a spin-1 Bose condensate, which exhibits Josephson dynamics in the spin populations that correspond in the mean-field limit to motion of a non-rigid mechanical pendulum. The condensate is initialized to a minimum uncertainty spin state corresponding to a unstable (hyperbolic) fixed point of the phase space, and quantum fluctuations lead to non-linear spin evolution along a separatrix. At early times, we measure squeezing in spin-nematic variables up to –8 dB [1]. At intermediate times, we measure spin oscillations characterized by non-Gaussian probability distributions that are in good agreement with exact quantum calculations up to 0.25 s. At longer times, atomic loss due to the finite lifetime of the condensate leads to larger spin oscillation amplitudes compared to no loss case as orbits depart from the separatrix [2]. This experiment demonstrates how decoherence of a many-body system can result in more apparent coherent behavior.

References

[1] Hamley, C. D., Gerving, C. S., Hoang, T. M., Bookjans, E. M., and Chapman, M. S., *Spin-nematic squeezed vacuum in a quantum gas*, Nature Phys. , 305–308 (2012).
[2] Gerving, C. S., Hoang, T. M., Land, B. J., Anquez, M., Hamley, C. D., and Chapman, M. S., *Non-equilibrium dynamics of an unstable quantum pendulum*, arXiv:1205.2121v1 [cond-mat.quant-gas].

Non-adiabatic preparation of spin crystals with ultracold polar molecules

Mikhail Lemeshko[1,2,*], Roman V. Krems[3], and Hendrik Weimer[1,2]

1. ITAMP, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2. Physics Department, Harvard University, 17 Oxford Street, Cambridge, MA 02138, USA
3. Department of Chemistry, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
**mikhail.lemeshko@gmail.com*

We study the growth dynamics of ordered structures of strongly interacting polar molecules in optical lattices. Using dipole blockade of microwave excitations, we map the system onto an interacting spin-1/2 model possessing ground states with crystalline order, and describe a way to prepare these states by non-adiabatically driving the transitions between molecular rotational levels. The proposed technique bypasses the need to cross a phase transition and allows for the creation of ordered domains of considerably larger size compared to approaches relying on adiabatic preparation.

We discuss the possibilities to use the dipole blockade of microwave excitations to create dissipation-induced bound states of polar molecules, and to cool an ultracold gas directly into a strongly-interacting many-body phase.

Reference

[1] M. Lemeshko, R. V. Krems, H. Weimer, arXiv:1203.0010 (2012).

Thermodynamics of Spin 3 ultra-cold atoms with free magnetization

L. Vernac, B. Pasquiou, E. Maréchal, O. Gorceix, and B. Laburthe-Tolra

Laboratoire de Physique des Laser, CNRS/Université Paris13, Villetaneuse, France
**laurent.vernac@univ-paris13.fr*

We study thermodynamic properties of a gas of spin 3 ^{52}Cr atoms across Bose Einstein condensation. Magnetization is free, due to dipole-dipole interactions. We show that the critical temperature for condensation is lowered at extremely low magnetic fields, when the spin degree of freedom is thermally activated [1]. The depolarized gas condenses in only one spin component, unless the magnetic field is set below a critical value Bc, below which a non-ferromagnetic phase is favoured due to spin dependent contact interactions [2]. We measure the magnetization of the gas versus the temperature; our results are compatible with predictions made respectively for a non-interacting gas with free magnetization above Bc, and for a non-interacting gas with fixed magnetization below Bc. In that case we obtain a hint for a double phase transition as predicted in [3]. In addition we demonstrate above Bc a spin thermometry efficient even below the degeneracy temperature.

References
[1] B. Pasquiou *et al.*, Phys. Rev. Lett. **108**, 045307 (2012).
[2] B. Pasquiou *et al.*, Phys. Rev. Lett **106**, 255303 (2011).
[3] T. Isoshima, T. Ohmi and K. Machida, J. Phys. Soc. Jpn. **69**, 3864 (2000).

Bose-Einstein condensation of erbium

K. Aikawa[1], A. Frisch[1], M. Mark[1], S. Baier[1], A. Rietzler[1], R. Grimm[1,2], and F. Ferlaino[1]

1. Institut für Experimentalphysik and Zentrum für Quantenphysik,
Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
2. Institut für Quantenoptik und Quanteninformation,
Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria

We report on the achievement of the first Bose-Einstein condensation (BEC) of erbium atoms. This unconventional atomic species belonging to the lanthanide series possesses a large magnetic moment of seven Bohr magneton, making this species an ideal system for studying novel quantum phenomena arising from strong dipole-dipole interaction. Atoms captured in a magneto-optical trap operating on the intercombination line are directly loaded into an optical dipole trap (ODT). Evaporative cooling in an ODT shows a remarkable efficiency, allowing us to achieve a pure condensate containing 7×10^4 atoms. In addition, a Feshbach resonance found at a very low magnetic field of around 1 G allows us to tune the contact interaction precisely. When the contact interaction is tuned close to zero, we observe a *d*-wave collapse of the Bose-Einstein condensate, which provides a striking signature of strongly dipolar quantum gases, as previously shown in the Stuttgart experiment for chromium.

Quantum phases and anomalous hysteresis of dipolar Bose gases in a triangular optical lattice

Daisuke Yamamoto[1,*], Ippei Danshita[2], and Carlos A. R. Sá de Melo[3]

1. Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
2. Computational Condensed Matter Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
3. School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
**d-yamamoto@riken.jp*

In recent years, increasing interest is devoted to the physics of ultracold gases with dipole-dipole interactions. We study the quantum phases and the hysteresis behavior of a dipolar Bose gas loaded into a triangular optical lattice [1]. Applying a large-size cluster mean-field method to the corresponding extended Bose-Hubbard model, we find that the interplay between the long-range interaction (proportional to $1/r^3$) and the frustrated geometry provides a rich variety of quantum phases, including some different solid and supersolid phases. We find that the transitions from supersolids to uniform superfluid are of first-order unlike the square-lattice case. It is also found that the system exhibits an anomalous hysteresis behavior, in which the transition can occur only unidirectionally [2], in the re-entrant first-order transition between superfluid and solid (or supersolid) phases.

References

[1] C. Becker *et. al*., *Ultracold quantum gases in triangular optical lattices* , New J. Phys. **12**, 065025 (2010).
[2] D. Yamamoto, I. Danshita, and C. A. R. Sá de Melo, *Dipolar bosons in triangular optical lattices: Quantum phase transitions and anomalous hysteresis*, Phys. Rev. A **85**, 021601(R) (2012).

Properties of ultracold ground state LiCs molecules

Marc Repp[1,*], Johannes Deiglmayr[2], Anna Grochola[3], Olivier Dulieu[4], Roland Wester[5], and Matthias Weidemüller[1]

1. Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg
2. Laboratory of Physical Chemistry, Eidgenössische Technische Hochschule Zürich
3. Institute of Experimental Physics, University of Warsaw,
4. Laboratoire Aimé Cotton, CNRS/Université Paris-Sud, Orsay, France
5. Institut für Ionenphysik und Angewandte Physik, University of Innsbruck
**repp@physi.uni-heidelberg.de*

Ultracold LiCs molecules in the absolute ground state $X^1\Sigma^+$, $v''=0$, $J''=0$ were formed in a MOT by a single photo-association step [1]. The dipole moment of ground state levels has been determined and was found to be in excellent agreement with theoretical predictions [2,3]. We present also the creation of LiCs molecules directly in an optical dipole trap. Rate coefficients for inelastic collisions between deeply bound LiCs molecules [4] and cesium atoms are measured and the results are compared with predictions from the universal model of Idziaszek and Julienne [5]. We will also show experimental evidence for the occurrence of redistribution processes of internal states in a trapped sample of ultracold LiCs molecules driven by black-body radiation and spontaneous decay [6].

References

[1] J. Deiglmayr *et al*., Phys. Rev. Lett. 101, 133004 (2008).
[2] M. Aymar, O. Dulieu, J. Chem. Phys. 122, 204302 (2005).
[3] J. Deiglmayr *et al*., Phys. Rev. A 82, 032503 (2010).
[4] J. Deiglmayr *et al*., Phys. Chem. Chem. Phys.13, 19101 (2011).
[5] Z. Idziaszek & P. Julienne, Phys. Rev. Lett. 104, 113202 (2010).
[6] J. Deiglmayr *et al*., Eur. Phys. J. D 65, 99 (2011).

Formation of ultracold fermionic NaLi Feshbach molecules

Myoung-Sun Heo[1], Tout T. Wang[1,2], Caleb A. Christensen[1], Timur M. Rvachov[1],
Dylan A. Cotta[1,3], Jae-Hoon Choi[1], Ye-Ryoung Lee[1], and Wolfgang Ketterle[1]

1. MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2. Department of Physics, Harvard University, Cambridge, MA 02138, USA
3. Département de Physique, École Normale Supérieure de Cachan, 94235 Cachan, France

We describe the formation of fermionic NaLi Feshbach molecules from an ultracold mixture of bosonic ^{23}Na and fermionic ^{6}Li [1]. Precise magnetic field sweeps across a narrow Feshbach resonance at 745 G result in a molecule conversion fraction of 5% for our experimental densities and temperatures, corresponding to a molecule number of 5×10^4. The observed molecular decay lifetime is 1.3 ms after removing free Li and Na atoms from the trap.

Reference

[1] M.-S. Heo *et al.*, arXiv:1205.5304v1 [cond-mat.quant-gas].

Soliton lattices in dipolar Bose-Einstein condensates

YuanYao Lin* and Ray-Kuang Lee

Institute of Photonics Technologies, National Tsing-Hua Univeristy, Hsinchu, 300, Taiwan
**yuyalin@mx.nthu.edu.tw*

With the long-ranged dipole-dipole interaction, in this work, we investigate the formation of periodic soliton solutions, named as the soliton lattices, in both quasi-one- and two-dimensional dipolar Bose-Einstein condensates [1,2]. Due to the balance between the mean-field and dipole-dipole interaction, a crystallization of bright solitons can be formed in the lattice structure, which reveals a lower system Hamiltonian energy than that of isolated solitons. Moreover, the parameters space to support the therefore formed crystallized structure is characterized for the possible experimental realizations.

References

[1] A. Griesmaier, J. Werner, S. Hensler, J. Stuhler, and T. Pfau, *Bose-Einstein Condensation of Chromium,* Phys. Rev. Lett. **94**, 160401 (2005).
[2] Luis E. Young-S, P. Muruganandam and S. K. Adhikari, *Dynamics of quasi-one-dimensional bright and vortex solitons of a dipolar Bose–Einstein condensate with repulsive atomic interaction*, J. Phys. B: At. Mol. Opt. Phys. **44**, pp. 101001 (2011).

Spin-injection spectroscopy of a spin-orbit coupled Fermi gas

Lawrence W. Cheuk[1,*], Ariel T. Sommer[1], Zoran Hadzibabic[1,2], Tarik Yefsah[1], Waseem S. Bakr[1], and Martin W. Zwierlein[1]

1. Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, MIT, Cambridge, Massachusetts, USA
2. Cavendish Laboratory, University of Cambridge, Cambridge, UK
**lcheuk@mit.edu*

The coupling of the spin of electrons to their motional state lies at the heart of recently discovered topological phases of matter. We create and detect spin-orbit coupling in an atomic Fermi gas, a highly controllable form of quantum degenerate matter. We reveal the spin-orbit gap via spin-injection spectroscopy, which characterizes the energy-momentum dispersion and spin composition of the quantum states. For energies within the spin-orbit gap, the system acts as a spin diode. To fully inhibit transport, we open an additional spin gap, thereby creating a spin-orbit coupled lattice whose spinful band structure we probe. In the presence of s-wave interactions, such systems should display induced p-wave pairing, topological superfluidity, and Majorana edge states.

Reference

[1] L. W. Cheuk *et al.*, preprint arXiv:1205.3483v1 [cond-mat.quant-gas] (2012).

Towards local probing of ultracold Fermi gases

Kai Morgener*, Wolf Weimer, Jan Henning Drewes, Niels Strohmaier, and Henning Moritz

Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg
**kmorgene@physnet.uni-hamburg.de*

Ultracold fermionic gases are an ideal model system for the study of quantum many-body phenomena. Of particular interest are two-dimensional strongly correlated systems which can exhibit superfluidity and Berezinskii-Kosterlitz-Thouless-type transitions.

Here we present our new experimental setup aimed at studying two-dimensional strongly interacting Fermi gases. Lithium atoms are cooled all-optically using an in vacuo bow-tie resonator for high transfer and cooling efficiency. The quantum degenerate gas will then be placed between two high resolution microscope objectives for local readout and control. The present status of the experiment will be shown.

Mesoscopic transport of ultracold fermions through an engineered channel

Martin Bruderer* and Wolfgang Belzig

Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany
**martin.bruderer@uni-konstanz.de*

Experiments with ultracold fermions flowing through a narrow channel between two macroscopic reservoirs [1] have recently extended the concept of quantum simulation to mesoscopic physics. We report on a theoretical study [2] of such a setup, where the channel and the reservoirs consist of optical lattices. We describe the full equilibration process between the reservoirs — for finite temperatures and arbitrarily strong channel-reservoir couplings — using the Landauer formalism and non-equilibrium Green's functions. Our detailed analysis reveals significant quantum and thermal fluctuations of the atomic current despite intrinsic damping mechanisms. Moreover, we show how to control the current by either engineering specific optical lattice potentials or tuning the interactions between the fermions. As a result of the high control and slow dynamics of the equilibration process these new systems provide a versatile testbed for studying quantum transport.

References

[1] J.-P. Brantut, J. Meineke, D. Stadler, S. Krinner and T. Esslinger, *Conduction of ultracold fermions through a mesoscopic channel*, Preprint arXiv:1203.1927.
[2] M. Bruderer and W. Belzig, *Mesoscopic transport of fermions through an engineered optical lattice connecting two reservoirs*, Phys. Rev. A **85**, 013623 (2012).

Two-component Fermi gas of unequal masses at unitarity: a quantum Monte Carlo approach

J. Boronat[1,]*, G. E. Astrakharchik[1], and S. Giorgini[2]

1. Departament de Física i Enginyeria Nuclear, Campus Nord B4-B5, Universitat Politècnica de Catalunya, E-08034 Barcelona, Spain
2. Dipartimento di Fisica, Università di Trento and INO-CNR BEC Center, I-38050 Povo, Trento, Italy
**jordi.boronat@upc.edu*

We have studied the zero-temperature stability of a two-component Fermi gas at unitarity ($1 / k_F a = 0$) when the mass of the two components is different. To this end, we have carried out extensive calculations of the microscopic properties of the gas as a function of the mass ratio of heavy M to light m components using the fixed-node diffusion Monte Carlo method. This method has been used previously to characterize the unitary limit predicting results in close agreement with experiment [1]. Now, we extend our study to the case of different masses. Our many-body results show that the Fermi gas in this particular limit becomes unstable with respect to the formation of clusters when $M / m \geq 13(1)$. This instability is observed in a normal phase and is absent in simulations of a superfluid state. This interesting result is elucidated by analyzing the shape of the nodal surface of the three-body problem.

Reference

[1] G. E. Astrakharchik, J. Boronat, J. Casulleras, S. Giorgini, *Equation of State of a Fermi Gas in the BEC-BCS Crossover: A Quantum Monte Carlo Study*, Phys. Rev. Lett. **93**, 200404 (2004).

An impurity in a Fermi sea on a narrow Feshbach resonance: a variational study of the polaronic and dimeronic branches

Christian Trefzger* and Yvan Castin

Laboratoire Kastler Brossel, École Normale Supérieure and CNRS, UPMC, 24 rue Lhomond, 75231 Paris, France
**christian.trefzger@lkb.ens.fr*

We study the problem of a single impurity of mass M immersed in a Fermi sea of particles of mass m [1]. The impurity and the fermions interact through a s-wave narrow Feshbach resonance, so that the Feshbach length R_* naturally appears in the system. We use simple variational ansatz, limited to at most one pair of particle-hole excitations of the Fermi sea and we determine for the polaronic and dimeronic branches the phase diagram between absolute ground state, local minimum, thermodynamically unstable regions (with negative effective mass), and regions of complex energies (with negative imaginary part). We also determine the closed channel population which is experimentally accessible. Finally we identify a non-trivial weakly attractive limit where analytical results can be obtained, in particular for the crossing point between the polaronic and dimeronic energy branches.

Reference

[1] Christian Trefzger, Yvan Castin *An impurity in a Fermi sea on a narrow Feshbach resonance: A variational study of the polaronic and dimeronic branches*, arXiv:1112.4364.

Fermionic Q-functions

Laura Rosales-Zarate and Peter D. Drummond*

Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne 3122, Victoria, Australia
**pdrummond@swin.edu.au*

The Q-function for bosons allows all possible observables to be obtained from a unique positive probability distribution. This means that bosonic coherence and correlations can be readily obtained in a probabilistic way. We show that a Q-function is also possible for fermions, which can generate all moments and correlations in one distribution. This requires an approach that is more general than the Gilmore-Perelemov fermion coherent state. We obtain a Q-function by tracing SU(N) Gaussian operators combined with a Haar measure and a fermion density operator. Unlike previous definitions, this leads to a unique, positive phase-space representation for all possible fermionic states. This complements previous results on a fermionic P-function [1], which has been successfully used to calculate the ground-state of the Hubbard model [2]. We investigate approaches to calculating and measuring the fermionic Q-function, including computational methods and tomographic experiments.

References

[1] J. F. Corney and P. D. Drummond, *Gaussian phase-space representations for fermions*, Phys. Rev. B **73** pp. 125112 (2006).
[2] Takeshi Aimi and Masatoshi Imada, *Does Simple Two-Dimensional Hubbard Model Account for High-Tc Superconductivity in Copper Oxides?*, J. Phys. Soc. Jpn. **76** pp. 113708 (2007).

Topological phase transition and Majorana fermions in spin-orbit coupled Fermi gases

Takeshi Mizushima[1,*], Takuto Kawakami[1], and Masatoshi Sato[2]

1. Department of Physics, Okayama University, Okayama 700-8530, Japan
2. The Institute for Solid State Physics, The University of Tokyo, Chiba, 277-8581, Japan
**mizushima@mp.okayama-u.ac.jp*

We theoretically investigate the topological aspects of spin-orbit coupled Fermi gases under a Zeeman magnetic field. The most remarkable fact is that a chiral Majorana fermion emerges in the interface between topological and non-topological domains, suchas the edge and the singular vortex core [1]. Based on the Bogoliubov-de Gennes theory extended to the strong coupling regime, we first discuss the stability of the Majorana fermion bound at the edge of the array of a one-dimensional Fermi gas coupled with a non-Abelian gauge field, analogous to a junction system composed of quantum wire and *S*-wave superconductor. We also clarify the structure of chiral Majorana fermions inside the vortex core in the vicinity of the topological phase transition. The distinction from the results obtained in a spin-polarized Fermi gas with a *p*-wave Feshbach resonance [2] is discussed.

References

[1] M. Sato, *et al.*, Phys. Rev. Lett. **103**, 020401 (2009); Phys. Rev. B **82**, 134521 (2010).
[2] T. Mizushima, *et al.*, Phys. Rev. Lett. **101**, 150409 (2008); Phys. Rev. A **81**, 053605 (2010); *ibid* **82**, 023624 (2010).

Revealing the superfluid lambda transition in the universal thermodynamics of a unitary Fermi gas

Mark Ku*, Ariel Sommer, Lawrence Cheuk, and Martin Zwierlein

Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
**mku@mit.edu*

We have observed the superfluid phase transition in a strongly interacting Fermi gas via high-precision measurements of the local compressibility, density and pressure down to near-zero entropy. We perform the measurements by in-situ imaging of ultracold ^{6}Li at a Feshbach resonance. Our data completely determine the universal thermodynamics of strongly interacting fermions without any fit or external thermometer. The onset of superfluidity is observed in the compressibility, the chemical potential, theentropy, and the heat capacity. In particular, the heat capacity displays a characteristic lambda-like feature at the critical temperature of T_c / T_F = 0.167(13). This is the first direct thermodynamic signature of the superfluid transition in a spin-balanced atomic Fermi gas. We measure the ground-state energy of the superfluid to be $3 / 5\xi N E_F$, with $\xi = 0.376(4)$. The experimental results are compared to recent Monte-Carlo calculations. Our measurements provide a benchmark for many-body theories on strongly interacting fermions, relevant for problems ranging from high-temperature superconductivity to the equation of state of neutron stars.

Spin-depairing transition in one-dimensional two-component Fermi gases

Shun Uchino[1,*] and Norio Kawakami[2]

1. DPMC-MaNEP, University of Geneva, 24 Quai Ernest-Ansermet, 1211 Geneva, Switzerland
2. Department of Physics, Kyoto University, Kyoto 606-8502, Japan
**Shun.Uchino@unige.ch*

We investigate one-dimensional two-component Fermi gases with a time-dependent gauge field on the spin sector. It is known that the ground state of two-component attractive Fermi gases is filled with bound states of up-spin and down-spin particles and the spin excitation has a gap, which is attributed to the appearance of fermionic superfluidity. By combining the methods of the Bethe ansatz with complex twists and Landau-Dykhne, we show that a spin-depairing transition occurs, which may represent a nonequilibrium transition from fermionic superfluids to normal states with spin currents. We analyze cases of Fermi-Hubbard and Yang-Gaudin models, and show how filling (density) affects the transition probability.

Reference

[1] S. Uchino and N. Kawakami, Phys. Rev. A **85**, 013610 (2012).

Higher order longitudinal collective oscillations in a strongly interacting Fermi gas

Leonid Sidorenkov[1,2,*], Meng Khoon Tey[1,2], Edmundo Sanchez[1,2] and Rudolf Grimm[1,2]
Yanhua Hou[3], Lev Pitaevskii[3,4], and Sandro Stringari[3]

1. Institut für Quantenoptik and Quanteninformation, Österreichische Akademie der Wissenschaften, Innsbruck, Austria
2. Institut für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria
3. Università di Trento and INO-CNR BEC Center, Povo, Italy
4. Kapitza Institute for Physical Problems, Moscow, Russia
**leonid.sidorenkov@uibk.ac.at*

Measuring the collective oscillation frequencies of a trapped atomic gas is a useful tool to probe its thermodynamic properties. Previously, this technique was performed only with the lowest order collective modes, namely the surface modes (e.g. sloshing and quadrupole modes), and the breathing modes. Higher longitudinal modes with richer nodal structures *inside* the cloud have not been investigated mainly because of the difficulty to excite such modes. Here, we present our study on the higher longitudinal collective modes in an elongated cloud of a Fermi gas with unitarity-limited interactions. Unlike the lowest order modes which are temperature independent, these modes can be used to probe the Equation of State (EoS) of the gas at higher temperatures. We performed precise measurement of the oscillation frequencies, and observed a good agreement between our measurements and the predictions using the EoS measured by the MIT group [1].

Reference

[1] Mark J. H. Ku *et al.*, Science 335, 563-567 (2012).

Towards strongly repulsive fermionic potassium

Alma B. Bardon, Nathan Cheng, Stefan Trotzky, and Joseph H. Thywissen

Department of Physics, University of Toronto, 60 Saint George St., Toronto, Ontario, Canada, M5S 1A7

A degenerate gas of fermionic atoms at its Feshbach resonance provides a clean and versatile system to study topics such as ferromagnetism, resonant superfluids, and few-body bound states. Our experiment consists of a crossed dipole trap below a microfabricated chip. The chip provides a tight magnetic trap for the initial stage of evaporative cooling. After transfer to the optical trap, it serves as a source of strong magnetic gradients, RF fields, and microwaves to manipulate the atoms. We will discuss several improvements to our apparatus, and report on our progress towards strongly interacting gases.

Anomalous concentration of atoms in standing light wave

D. V. Brazhnikov[1,2,*], A. N. Goncharov[1,2,3], R. Ya. Ilenkov[1], N. A. Koliada[1], O. N. Prudnikov[2], A. M. Shilov[1,2], A. V. Taichenachev[1,2], A. M. Tumaikin[1], V. I. Yudin[1,2,3], and A. S. Zibrov[2,4]

1. Institute of Laser Physics SB RAS, Novosibirsk, Russia
2. Novosibirsk State University, Novosibirsk, Russia
3. Novosibirsk State Technical University, Novosibirsk, Russia
4. Harvard University, Cambridge, Massachusetts, USA
**LLF@laser.nsc.ru*

Steady-state momentum and coordinate distributions of two-level atoms under a standing light wave are explored. Theoretical results are calculated by applying the new method for finding a solution of quantum kinetic equation [1]. The method allows one to take into account recoil effects entirely for the light field of arbitrary intensity. In the case of weak field we gain a well-known result: the atoms are located in vicinity of the standing wave's antinodes, i.e. in minima of the quasiclassical optical potential (the laser field detuning is meant to be red). However, in the case of strong field a new effect is revealed: high concentration of atoms occurs at the nodes, i.e. at the maxima of the optical lattice potential. The qualitative interpretation of the results is given. The result provides throwing light on some features of atomic kinetics under strong light waves and may be found useful in atomic optics and nanolithography.

Reference

[1] O. N. Prudnikov, R. Ya. Il'enkov, A. V. Taichenachev, A. M. Tumaikin and V. I. Yudin, "Steady state of a low-density ensemble of atoms in a monochromatic field taking into account recoil effects", J. Exp. Theor. Phys. **112**(6), pp. 939-945 (2011).

Klein-tunneling of a quasirelativistic Bose-Einstein Condensate in an optical lattice

C. Grossert*, M. Leder, T. Salger, S. Kling, and M. Weitz

Institute for Applied Physics, University of Bonn, Germany
**grossert@iap.uni-bonn.de*

A proof-of-principle experiment simulating effects predicted by relativistic wave equations with ultracold atoms in a bichromatic optical lattice that allows for a tailoring of the dispersion relation is reported [1]. In this lattice, for specific choices of the relativistic phases and amplitudes of the lattice harmonics the dispersion relation in the region between the first and the second excited band becomes linear, as known for ultrarelativistic particles. One can show that the dynamicscan be described by an effective one-dimensional Dirac equation [2].

We experimentally observe the analog of Klein-Tunneling, the penetration of relativistic particles through a potential barrier without the exponential damping that is characteristic for nonrelativistic quantum tunneling [3]. Both linear (relativistic) and quadratic (nonrelativistic) dispersion relations are investigated, and significant barrier transmission is only observed for the relativistic case.

References
[1] T. Salger *et al.*, Phys. Rev. Lett. **107**, 240401 (2011).
[2] D. Witthaut *et al.*, Phys. Rev. A **84**, 033601 (2011).
[3] O. Klein, Z.Physik **53**, pp. 157-165 (1929).

Negative absolute temperature for motional degrees of freedom

Simon Braun[1,*], Philipp Ronzheimer[1], Michael Schreiber[1], Sean Hodgman[1], Tim Rom[1], Immanuel Bloch[1,2], and Ulrich Schneider[1]

1. Ludwig-Maximilians-Universität München, Germany
2. Max-Planck-Institut für Quantenoptik, Garching, Germany

Absolute temperature is one of the central concepts in statistical mechanics and is usually described as being strictly non-negative. However, in systems with an upper energy bound, also negative temperature states can be realized. In these states, the occupation probability of each basis state increases with energy. So far, they have been demonstrated only for localized degrees of freedom such as the spin of nuclei or atoms [1,2]. By using a Feshbach resonance in bosonic ^{39}K, we implemented the attractive Bose-Hubbard model in a three-dimensional optical lattice. Following a recent proposal [3,4], we were able to create a negative temperature state for motional degrees of freedom, strikingly resulting in a condensate at the upper band edge of the lowest band. This attractively interacting bosonic superfluid is thermodynamically stable, i.e. stable against mean-field collapse for abitrary atom numbers. We additionally investigated the characteristic timescale for the emergence of coherence in the ensemble, and found an intriguing symmetry between the negative temperature and positive temperature state.

References
[1] A. S. Oja *et al.*, Rev. Mod. Phys. **69**, 1 (1997).
[2] P. Medley *et al.*, Phys. Rev. Lett. **106**, 195301 (2011).
[3] A. Rapp *et al.*, Phys. Rev. Lett. **105**, 220405 (2010).
[4] A. P. Mosk, Phys. Rev. Lett. **95**, 040403 (2005).

Tunable gauge potential for spinless particles in driven lattices

J. Simonet[1,*], J. Struck[1], M. Weinberg[1], C. Ölschläger[1], P. Hauke[2], A. Eckardt[3], P. Windpassinger[1], M. Lewenstein[2], and K. Sengstock[1]

1. Institut für Laserphysik, Universität Hamburg, Hamburg, Germany
2. Institut de Ciències Fotòniques, Barcelona, Spain
3. Max-Planck-Institut für Physik komplexer Systeme, Dresden, Germany
**jsimonet@physnet.uni-hamburg.de*

We present a universal method to create a tunable, artificial vector gauge potential for neutral particles trapped in an optical lattice. A suitable periodic shaking of the lattice allows to engineer a Peierls phase for the hopping parameters. This schemethus allows one to address the atomic internal degrees of freedom independently. We experimentally demonstrate the realization of such artificial potentials in a 1D lattice, which generate ground state superfuids at arbitrary non-zero quasi-momentum [1].

This scheme offers fascinating possibilities to emulate synthetic magnetic fields in 2D lattices. In a triangular lattice, continuously tunable staggered fluxes are realized. Spontaneous symmetry-breaking has recently been observed for a π-flux [2]. With the presented scheme, we are now able to study the influence of a small symmetry-breaking perturbation.

References

[1] J. Struck *et al.*, arXiv:1203.0049 (2012).
[2] J. Struck *et al.*, Science **333**, 996 (2011).

Robust critical states appear in ultra-cold atom gases

M. Takahashi[1,*], H. Katsura[1], M. Kohmoto[2], and T. Koma[1]

1. Department of Physics, Gakushuin Universisty, Tokyo 171-8588, Japan
2. Institute for Solid Stte Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan
**masahiro.takahashi@gakushuin.ac.jp*

We theoretically study the stationary states for the nonlinear Schrödinger equation on the Fibonacci lattice which is expected to be realized by Bose-Einstein condensates loaded into an optical lattice. Such a quasiperiodic system is realizable by using recently developed method for creating potentials through a holographic mask [1]. When the model does not have a nonlinear term, the wavefunctions and the spectrum are known to show fractal structures [2]. Such wavefunctions are called critical.

In our study, we numerically solve the nonlinear Schrödinger equation on the one-dimensional Fibonacci lattice and propose some mathematical theorems to present a phase diagram of the energy spectrum for varying the nonlinearity. The phase diagram consists of three portions, a forbidden region, the spectrum of critical states, and the spectrum of stationary solitons. Critical states are considered fragile in perturbations in general. However, we show that the energy spectrum of critical states remains intact irrespective of the nonlinearity in the sea of a large number of stationary solitons. We expect the first direct detection of the critical state in the ultra-cold atom gases.

References

[1] W. S. Bakr, J. I. Gillen, A. Peng, S. Folling, and M. Greiner, Nature **462**, 74 (2009).
[2] M. Kohmoto, B. Sutherland, and C. Tang, Phys. Rev. B **35**, 1020 (1987).
[3] M. Takahashi, H. Katsura, M. Kohmoto, and T. Koma, arXiv:1110.6328.

Strong suppression of transport due to quantum phase slips in 1D Bose gases

Ippei Danshita[1,*] and Anatoli Polkovnikov[2]

1. Computational Condensed Matter Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
2. Department of Physics, Boston University, Boston, Massachusetts 02215, USA
**danshita@riken.jp*

Recent experiments [1, 2, 3] have intensively investigated the transport of 1D Bose gases in optical lattices and shown that the transport in 1D is drastically suppressed even in the superfluid state compared to that in higher dimensions. Motivated by the experiments, we study the superflow decay of 1D Bose gases via quantum nucleation of phase slips by means of both analytical instanton techniques and numerically exact time-evolving block decimation method. We find that the nucleation rate Γ of a quantum phase slip in an optical lattice exhibits a power-law behavior with respect to the flow momentum p as $\Gamma / L \propto p^{2K-2}$ when $p << \hbar / d$, where L, K, and d denote the system size, the Luttinger parameter, and the lattice spacing [4]. To make a connection with the experiments, we relate the nucleation rate with the damping rate of dipole oscillations in a trapped system, which is a typical experimental observable [1, 2], and show that the suppression of the transport in 1D is due to quantum phase slips. We also suggest a way to identify the superfluid-insulator transition point from the dipole oscillations.

References
[1] C. D. Fertig *et al.*, Phys. Rev. Lett. **94**, 120403 (2005).
[2] E. Haller *et al.*, Nature **466**, 597 (2010).
[3] B. Gadway, D. Pertot, J. Reeves, M. Vogt, and D. Schneble, Phys. Rev. Lett **107**, 145306 (2011).
[4] I. Danshita and A. Polkovnikov, Phys. Rev. A **85**, 023638 (2012).

Generation of tunable correlated atom beams in an optical lattice

Marie Bonneau*, Josselin Ruaudel, Raphael Lopes, Jean-Christophe Jaskula, Alain Aspect, Denis Boiron, and Chris Westbrook

Laboratoire Charles Fabry de l'Institut d'Optique, Université Paris-Sud, CNRS,
2 av. Augustin Fresnel, Campus Polytechnique, 91127 Palaiseau, France
**marie.bonneau@institutoptique.fr*

Spontaneous four wave mixing (SFWM) of matter waves is a source of non-classical atomic pair states, similar to the twin photon states generated through parametric down-conversion and widely used in quantum optics: Momentum correlations [1] and sub-shot noise relative number fluctuations [2] were demonstrated for atoms produced through SFWM in free space. Using a scheme similar to [3], we perform here SFWM in a moving 1D optical lattice, from a metastable helium quasi-BEC. Thus, pairs of atoms are efficiently scattered into two matter beams, whose momenta are precisely tunable. The ability to control the beam population makes this source suitable for a variety of quantum atom optics experiments, in the limit of either highor low mode population. We study the beams' correlation properties, which are crucial for such applications.

References
[1] A. Perrin *et al.*, *PRL* **99**, 150405 (2007).
[2] J.-C. Jaskula *et al.*, *PRL* **105**, 190402 (2010).
[3] G. K. Campbell *et al.*, *PRL* **96**, 020406 (2006).

Dynamic structure factor of Bose-Bose mixtures in an optical lattice

Takeshi Ozaki[1,*], Ippei Danshita[2], and Tetsuro Nikuni[1]

1. Department of Physics, Faculty of Science, Tokyo University of Science, Shinjuku, Tokyo, Japan
2. Computational Condensed Matter Physics Laboratory, RIKEN, Wako, Saitama, Japan
**j1209702@ed.kagu.tus.ac.jp*

Binary mixtures of Bose gases confined in an optical lattice have been realized in experiments [1]. Previous theoretical studies have predicted various quantum phases, including superfluid (SF), Mott insulator (MI), paired SF (PSF), and counterflow SF (CFSF) [2, 3]. We study elementary excitations of Bose-Bose mixtures in an optical lattice by analyzing the Bose-Hubbard model within the time-dependent Gutzwiller approximation. Applying a linear response theory, we calculate the density response functions of Bose-Bose mixtures in SF, PSF, and CFSF phases and show that characteristics of these phases are clearly manifested in the dynamical properties. We find that one-component density fluctuation induces the in-phase mode for the attractive interspecies interaction and the out-of-phase mode for the repulsive interspecies interaction.

References

[1] S. Trotzky, *et al.*, Science **319**, 295 (2008), J. Catani, *et al.*, Phys. Rev. A **77**, 011603(R) (2008).
[2] A. Kuklov, *et al.*, Phys. Rev. Lett. **92**, 030403 (2004); *ibid.* 92 050402 (2004).
[3] Anzi Hu, *et al.*, Phys. Rev. A **84**, 041609 (2011).

Optical lattices Mo-102

Optical flux lattices for ultra cold atoms using Raman transitions

G. Juzeliūnas[1,*] and I. B. Spielman[2]

1. Inst. Theor. Phys. and Astronomy, Vilnius University, A. Goštauto 12, Vilnius LT-01108, Lithuania
2. Joint Quantum Institute, NIST and University of Maryland, Gaithersburg, Maryland, 20899, USA
**gediminas.juzeliunas@tfai.vu.lt*

We theoretically investigate the optical flux lattices [1,2] produced for ultra-cold atoms subject to laser fields where both the atom-light coupling and the effective detuning are spatially periodic. We explore the geometric vector potential and the magnetic flux it generates, as well as the accompanying geometric scalar potential. We show how to understand the gauge-dependent Aharonov-Bohm singularities in the vector potential, and calculate the continuous magnetic flux through the elementary cell in terms of these singularities. The analysis is illustrated with a square optical flux lattice. We conclude with an explicit laser configuration yielding such a lattice using a set of five properly chosen beams with two pairs counter propagating along $\mathbf{e}_x$, and $\mathbf{e}_y$ along with a single beam along $\mathbf{e}_z$. We show that this lattice is not phase-stable, and identify the one phase-difference that affects the magnetic flux. Thus armed with realistic laser setup, we directly compute the Chern number of the lowest Bloch band to identify the region where the non-zero magnetic flux produces a topologically non-trivial band structure.

References

[1] J. Dalibard, F. Gerbier and G. Juzeliūnas and P. Öhberg, *Artificial gauge potentials for neutral atoms*, Rev. Mod. Phys. **83**, pp. 1523-1543 (2011).
[2] N. R. Cooper, *Optical Flux Lattices for Ultracold Atomic Gases*, Phys. Rev. Lett. **106**, p. 175301-1–4 (2011).

Non-equilibrium dynamics, heating, and thermalization of atoms in optical lattices

Andrew Daley[1], Johannes Schachenmayer[1,2,3], Hannes Pichler[2,3], Lode Pollet[4], Matthias Troyer[5], and Peter Zoller[2,3]

1. Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, USA
2. Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria
3. IQOQI, Austrian Academy of Sciences, Innsbruck, Austria
4. Department of Physics, Ludwig-Maximilians-Universität München, München, Germany
5. Theoretische Physik, ETH Zürich, Zürich, Switzerland

A key challenge in current experiments with ultracold atoms is to produce low entropy many-body states in optical lattices. In this context, it is very important to characterize and control heating processes, which arise from various sources including spontaneous emissions and classical fluctuations of the lattice potential. These processes are intrinsically interesting, as there often a separation of timescales between some excitations that thermalize rapidly, and some that do not properly thermalize in the duration of an experimental run, so that the non-equilibrium many-body dynamics of thermalization play a crucial role. Here we first consider how different many-body states of bosons and fermions are sensitive to amplitude fluctuations of the lattice potential, and we show how a dressed lattice scheme could provide control over such noise for atoms in the lowest Bloch band of a lattice. We then present results on the thermalization of bosons in an optical lattice in the presence of spontaneous emissions.

Reservoir-assisted band decay of ultracold atoms in a spin-dependent optical lattice

David Chen*, Carolyn Meldgin, and Brian DeMarco

University of Illinois at Urbana Champaign, USA
**dchen30@illinois.edu*

We report measurements of reservoir-assisted decay of atoms in excited bands in a cubic, spin-dependent optical lattice. We adiabatically load a 87Rb BEC in a mixture of mF = 0 and mF = −1 states into a 3D lattice. Atoms in the mF = −1 state experience a strong lattice potential. On the contrary, atoms in the mF = 0 state form a harmonically trapped superfluid reservoir since they do not interact with the lattice. We transfer atoms in the mF = −1 state to the first excited band using stimulated Raman transitions, and we measure the decay rate to the ground band induced by collisions with the reservoir.

One-way quantum computation with ultra-narrow optical transition of ^{171}Yb atoms

Akimasa Nakamoto[1,*], Miranda Martin[1], Yuki Okuyama[1], Atsushi Noguchi[1,*], Masahito Ueda[2], and Mikio Kozuma[1]

1. Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo, Japan
2. University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
**nakamoto.a.aa@m.titech.ac.jp*
† Present Affiliation: Osaka University

Multi-particle cluster state was successfully created for rubidium atoms, by using an electronic spin dependent potential[1]. Creation of the cluster state for nuclear spin is desirable because of its long coherence time. Here we present a method to create a cluster state for nuclear spins of ^{171}Yb atoms by using ultra-narrow optical transition ($^1S_0 \leftrightarrow {}^3P_2$, λ = 507nm). While this transition has an extremely narrow line-width of 10mHz, our calculation says a potential depth of 10μK can be created using laser power of 100mW, where the detuning and the beam waist are set to 150kHz and 30μm, respectively. Since the $^3P_2$ excited state has a large hyperfine splitting(6.7GHz), the potential is dependent on the nuclear spin state. We experimentally generated 507nm of the second harmonic light using a PPKTP crystal, where a fundamental light (1014nm) was prepared by using a laser diode and a tapered amplifier. Obtained power of the second harmonic light was 150mW which is enough to implement our plan.

Reference

[1] Olaf Mandel, Markus Greiner, Artur Widera, Tim Rom, Theodor W. Hänsch and Immanuel Bloch, *Controlled collisions for multi-particle entanglement of optically trapped atoms*, Nature **425** 934(2003).

High-resolution optical spectra of bosonic ytterbium atoms in an optical lattice: Comparison between numerical calculations and experiments

K. Inaba[1,3,*], M. Yamashita[1,3], S. Kato[2], K. Shibata[2], R. Yamamoto[2], and Y. Takahashi[2,3]

1. NTT Basic Research labs., NTT Corporation, Atsugi, Kanagawa 243-0198, Japan
2. Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
3. JST, CREST, Chiyoda-ku, Tokyo 102-0075, Japan
**inaba.kensuke@lab.ntt.co.jp*

We investigate laser spectra of bosonic ^{174}Yb atoms in a three dimensional optical lattice both theoretically and experimentally. With the aid of a ultra-narrow optical transition of the Yb atoms [1], high-resolution spectra are systematically measured by varying the lattice depth. We also perform the following numerical simulations; first, determine parameters of the bosonic Hubbard model with the *ab initio* manner; then, analyze this model based on the Gutzwiller approximation considering finite temperature effects; finally, calculate the excitation spectra described by the Lehman representation. Here we consider modifications of the model parameters due to the formation of two-body bound states induced by confinement of the lattice potential [2]. The numerical simulations clarify how the spectra change depending on both temperatures and lattice depths. By comparing the numerical results with the measured spectra, we discuss phase transitions of the present system at finite temperatures.

References

[1] S. Kato, *et al.*, accepted in Appl. Phys. B: Lasers and Optics (2012).
[2] H. P. Büchler, Phys. Rev. Lett. **104**, pp. 090402 (2010).

Analysis for diffusion of fermion in optical lattice by lattice oscillation

Motoyoshi Inoue*, Yusuke Nakamura, and Yoshiya Yamanaka

Department of Electronic and Photonic Systems, Waseda University
**local-fortokyo@suou.waseda.jp*

Many intriguing phenomena such as Mott insulator and antiferromagnetism have been observed in the cold fermion gas systems in the optical lattice. They are well described by the Hubbard model, whose numerical analyses are performed in various ways, e.g. Gutzwiller anzatz, density matrix renormalization, and quantum Monte Carlo methods and so on. Recent advance in experimental technique made it feasible to perform more complicated experiment. Fermion dynamics is slower than boson one due to the Pauli blocking, so the observation of Mott insulator transition for cold fermion systems is rather difficult. We analyze the Hubbard model in the optical lattice and perform numerical simulation with Gutzwiller anzatz. We calculate various observable quantities and compare them to experiments [1, 2]. In addition, we discuss the time scale of the diffusion and propose a possible method in which the observation of Mott insulator transition in experiments is easier.

References
[1] M. Köhl, H. Moritz, T. Stöferle, K. Günter, and T. Esslinger, Phys. Rev. Lett. 94 080403 (2005).
[2] R. Jördens, N. Strohmaier, K. Günter, H. Moritz, and T. Esslinger, Nature 455 204 (2008).

A diffusion Monte Carlo approach to boson hard-rods in 1D optical lattices

F. de Soto* and C. Gordillo

Departamento de Sistemas Fisicos, Quimicos y Naturales,
Universidad Pablo de Olavide, Sevilla, Spain
**fcsotbor@upo.de*

We present a zero-temperature quantum Monte Carlo calculation of a system of hard-rods trapped in a purely 1D optical lattice by means of a diffusion Monte Carlo calculation. This method provides a continuous treatment of the positions contrarily to the widely extended Bose-Hubbard (BH) models allowing for a direct comparison both with BH models and experimental results [1]. We shall analyze the phase-structure of the model and characterize the different phases by analising some of its correlation functions. We present an estimate of a superfluid density based on an extension of the winding number technique to zero temperature [2], although its meaning in a purely 1D system is yet unclear. The off-diagonal one body density matrix shall be used to argue the nature of this non-isolating phase.

References
[1] F. De Soto, C. Gordillo, Phys. Rev. A 85, 013607 (2012).
[2] C. Cazorla, J. Boronat, Phys. Rev., B 73, 224515 (2006).

Phase diagram of 1D fermionic optical lattices with spatially alternating interaction

Atsushi Yamamoto* and Seiji Yunoki

RIKEN Advanced Institute for Computational Science, Hyogo, Japan
**a-yamamoto@riken.jp*

Spatial control of on-site interaction within ultracold atomic optical lattices is realized in recent experiment [1]. We focus on simple systems with spatially alternating on-site intaractions. We present a phase diagram of 1D fermionic optical lattices with spatially alternating on-site interaction by using density matrix renormalization group (DMRG) method. Our model is described by simple Hubbard model with spatially alternating on-site interaction U_1 and U_2. Employing DMRG method, we calculate that local density profile, spin-spin correlation function, and binding-energy. Phase diagram shows gradually changing as a function of spatially alternating interaction i.e., we find metallic, ordered state, Mott insulator phases. We discuss various desiderata for properties of new phase, we calculate dynamical properties by using dynamical DMRG method [2]. We present multiple band structure due to the U_1/U_2. Furthermore, focus on phase boundary, we can find gapped state closed as linearly-approximated structure.

References

[1] R. Yamazaki, S. Taie, S. Sugawa, and Y. Takahashi, "Submicron Spatial Modulation of an Interatomic Interaction in a Bose-Einstein Condensate", Phys. Rev. Lett. **105**, 050405 (2010).
[2] A. Yamamoto, S. Yamada, M. Okumura, and M. Machida, "Spectral properties of trapped one-dimensional ultracold fermions loaded on optical lattices", Phys. Rev. A **84**, 043642 (2011).

High-rate entanglement of two ions using single photon detection

G. Hétet[1,*], L. Slodička[1], N. Röck[1], P. Schindler[1], M. Hennrich[1], and R. Blatt[1,2]

1. Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria
2. Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria
**gabriel.hetet@uibk.ac.at*

We will present our experimental observation of entanglement of two effectively meter distant atomic qubits using single photon interference [1]. A weak laser field is used to Raman scatter a single photon from two Barium ions that are Doppler cooled in the Lamb-Dicke regime. Ensuring that the two possible emission paths are indistinguishable at a single photon counter, we show that a single detection event projects the two-ion state into a maximally entangled Bell state [2]. We also demonstrate that we can control the phase of the entangled states by tuning the path length difference between the two photonic channels.

A two orders of magnitude increase in the entanglement generation rate was measured compared to remote entanglement schemes that use two-photon coincidence events. This result is important for efficient distribution of quantum information over long distances using trapped ion architectures.

References

[1] Cabrillo C., Cirac J. I. Garcia-Fernandez P., Zoller P. Physical Review A **59**, 1025-1033 (1999).
[2] Slodička L., Röck N., P. Schindler, Hennrich M., Hétet G., Blatt R., *in preparation*.

Heralded photonic interaction between distant single ions

Christoph Kurz[1,*], Jan Huwer[1,2], Michael Schug[1], Philipp Müller[1], and Jürgen Eschner[1,2]

1. Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany
2. ICFO – The Institute of Photonic Sciences, Castelldefels (Barcelona), Spain
**c.kurz@physik.uni-saarland.de*

Two single Ca^+ ions interact over 1 m distance through emission and absorption of single resonant photons. Single-photon emission in the sender ion is continuous or triggered; absorption in the receiver is signaled by a quantum jump. For continuous emission of photons at 393 nm, the sender ion is driven by lasers such that the short-lived $P_{3/2}$ level is populated. Decay to the $S_{1/2}$ ground state generates photons at 393 nm, of which ~ 3% are transmitted to another ion trap. The receiver ion is continuously laser-cooled, emitting fluorescence at 397 nm. Sudden drops in the fluorescence mark the absorption of single 393 nm photons, transferring the ion to the long-lived $D_{5/2}$ state. We observe such quantum jumps at up to 1 s^{-1} rate. For pulsed photon generation, the sender ion is optically pumped to the $D_{5/2}$ state. Then a laser pulse at 854 nm excites it to the short-lived $P_{3/2}$ level, releasing a single photon at 393 nm. Frequency, polarization, and temporal shape of the 393 nm photon are controlled by the exciting pulses. Correlation analysis of the pulsed photon generation and the quantum jumps is currently underway.

Mo-112 Quantum information

Development of ion-trap technologies for quantum control of multi-species ion chains

H.-Y. Lo, D. Kienzler, B. Keitch*, J. Alonso, F. Leupold, L. de Clercq, F. Lindenfelser, R. Oswald, M. Sepiol, and J. Home

Institute for Quantum Electronics, ETH Zürich, Zürich, Switzerland
**bkeitch@ethz.ch*

We are developing setups for quantum information processing, simulation, and state engineering with trapped atomic ions. We will trap beryllium and calcium ions simultaneously in segmented linear Paul traps. One system is optimised for quantum control and separation of ion strings. The second setup is a micro-scale surface-electrode trap operating at 4K. In-vacuum high-speed switches allow ultra-fast ion shuttling. For Be^+ we have developed a 7.2W source at 626nm, using sum-frequency generation; this is further frequency doubled with BBO crystals in resonant cavities. The lasers required for Ca^+ are commercial systems stabilised to custom optical cavities, with finesses up to 290 000. Fluorescence is detected from both ion species with high NA imaging systems, designed with in-vacuum objective lenses. A custom high-speed FPGA control system is under-development that will be used to generate phase-coherent pulses.

Coherent manipulation of optical properties in a hot atomic vapor of helium

S. Kumar[1,*], T. Lauprêtre[2], R. Ghosh[1], F. Bretenaker, and F. Goldfarb

1. School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110067, India
2. Laboratoire Aimé Cotton, CNRS-Université Paris Sud 11, 91405 Orsay Cedex, France
**skphysics@gmail.com*

It is well known that ultranarrow electromagnetically induced transparency (EIT) resonances can be observed in a Λ-system of metastable helium at room temperature using the $2^3S_1 \rightarrow 2^3P_1$ transition [1]. We report the experimental observation of another type of ultranarrow resonance, even slightly narrower than the EIT one, in the same system. It is shown to be due to coherent population oscillations in two coupled open two-level systems [2]. We also explore the physics of the $2^3S_1 \rightarrow 2^3P_0$ transition in two different tripod configurations, with the probe field polarization perpendicular and parallel to the quantization axis, defined by an applied weak transverse magnetic field. In the first case, the two dark resonances interact incoherently and merge together into a single EIT peak with increasing coupling power. In the second case, we observe destructive interference between the two dark resonances inducinga narrow absorption resonance at the line center [3].

References

[1] F. Goldfarb, J. Ghosh, M. David, J. Ruggiero, T. Chanelière, J.-L. Le Gouët, H. Gilles, R. Ghosh, and F. Bretenaker, Europhys. Lett. **82**, 54002 (2008).
[2] T. Lauprêtre, S. Kumar, P. Berger, R. Faoro, R. Ghosh, F. Bretenaker and F. Goldfarb, arXiv 1201.3742v1; Communicated (2012).
[3] S. Kumar, T. Lauprêtre, R. Ghosh, F. Bretenaker and F. Goldfarb, Phys. Rev. A **84**, 023811 (2011).

Quantum information Mo-114

Long-lived qubit from three spin-1/2 atoms

Rui Han[1,*], Niels Lörch[1,2], Jun Suzuki[3], and Berthold-Georg Englert[1,4]

1. Centre for Quantum Technologies, NUS, 3 Science Drive 2, Singapore 117543, Singapore
2. Universität Heidelberg, Philosophenweg 16-19, 69120 Heidelberg, Germany
3. The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182-8585 Japan
4. Department of Physics, NUS, 2 Science Drive 3, Singapore 117542, Singapore
**han.rui@quantumlah.org*

A system of three spin-1/2 atoms allows the construction of a reference-frame-free (RFF) qubit in the subspace with total angular momentum $j = 1/2$. The RFF qubit stays coherent perfectly as long as the spins of the three atoms are affected homogeneously. The inhomogeneous evolution of the atoms causes decoherence, but this decoherence can be suppressed efficiently by applying a bias magnetic field of modest strength perpendicular to the plane of the atoms. The resulting lifetime of the RFF qubit can be many days, making RFF qubits of this kind promising candidates for quantum information storage units. Specifically, we examine the situation of three ^6Li atoms trapped in a CO_2-laser-generated optical lattice and find that, with conservatively estimated parameters, a stored qubit maintains a fidelity of 0.9999 for two hours.

References

[1] J. Suzuki, G. N. M. Tabia, and B.-G. Englert, Phys. Rev. A **78**, 052328 (2008).
[2] R. Han, N. Lörch, J. Suzuki and B.-G. Englert, Phys. Rev. A **84**, 012322 (2011).

Adiabatic passage at Rydberg blockade for single-atom loading and quantum gates

I. I. Beterov[1,*], I. I. Ryabtsev[1], D. B. Tretyakov[1], V. M. Entin[1], E. A. Yakshina[1], C. MacCormick[2], C. W. Mansell[2], and S. Bergamini[2]

1. Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia
2. Open University, Milton Keynes, UK
**beterov@isp.nsc.ru*

Mesoscopic ensembles of strongly interacting ultracold atoms trapped in optical lattices or in optical dipole trap arrays are promising candidates to implement a large-scale quantum register. Quantum information can be encoded in the collective states of atomic ensembles and processed by quantum logic gates exploiting Rydberg blockade of the laser excitation. If dipole traps or optical lattices are loaded from a cold atom cloud, the number of atoms in each site is random. Therefore, the frequency of Rabi oscillations between collective states of the atomic ensembles in the blockade regime is undefined, and single-atom excitation is not deterministic, as required for high-fidelity operations. We propose to use adiabatic passage to overcome the dependence of the Rabi frequency on the number of interacting atoms [1]. We show that both deterministic excitation of a single Rydberg atom and controlled-phase quantum gates can be implemented using chirped excitation or STIRAP in mesoscopic ensembles with unknown number of atoms. This allows for high-fidelity single-atom loading of optical lattices and quantum logic operations with randomly loaded ensembles.

Reference

[1] I. I. Beterov *et al.*, “Deterministic single-atom excitation via adiabatic passage and Rydberg blockade”, Phys. Rev. A **84**, 023413 (2011).

An elementary quantum network of single atoms in optical cavities

Carolin Hahn*, Stephan Ritter, Christian Nölleke, Andreas Reiserer, Andreas Neuzner, Manuel Uphoff, Martin Mücke, Eden Figuroa, Jörg Bochmann, and Gerhard Rempe

Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
**carolin.hahn@mpq.mpg.de*

Quantum networks are at the heart of quantum communication and distributed quantum computing. Single atoms trapped in optical resonators are ideally suited as universal quantum network nodes capable of sending, receiving, storing, and releasing photonic quantum information. The reversible exchange of quantum information between such single-atom cavity nodes is achieved by the coherent exchange of single photons. Here we present the first experimental realization of an elementary quantum network consisting of two atom-cavity nodes located in remote, independent laboratories [1]. We demonstrate the faithful transfer of arbitrary quantum states and the creation of entanglement between the two atoms. We characterize the fidelity and lifetime of the maximally entangled Bell states and manipulate the nonlocal state via unitary operations applied locally at one of the nodes. This cavity-based approach to quantum networking offers a clear perspective for scalability.

Reference

[1] S. Ritter *et al.*, “An elementary quantum network of single atoms in optical cavities”, Nature **484**, 195-200 (2012).

Addressable parallel quantum memory for light in cavity configuration

Anton Vetlugin* and Ivan Sokolov

Faculty of Physics, St. Petersburg State University, St. Petersburg, Russia
**vetluginanton@gmail.com*

We propose a cavity-based scheme for parallel spatially multimode quantum memory for light. A memory cell analogous to the previously proposed quantum volume hologram of [1] is placed into spatially multimode single-port ring cavity. The cell is illuminated with off-resonant counter-propagating quantum signal wave and strong classical reference wave. The cavity configuration allows for storage and retrieval with lower optical depth, and due to a uniform distribution of the field and spin amplitudes, the collective spin is excited more effectively. We reveal optimal temporal modes of the input quantized signal allowing for efficient state transfer to the memory degrees of freedom, and evaluate memory capacity in terms of the transverse modes number. We also describe a method of "on-demand", or addressable retrieval from the memory of quantized spatial modes, which is important [2] for application of memory in quantum repeaters.

References

[1] D. V. Vasilyev, I. V. Sokolov, and E. S. Polzik., *Quantum volume hologram.*, Phys. Rev. A, v. 81, 020302(R) (2010).
[2] C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden, and N. Gisin. *Quantum Repeaters with Photon Pair Sources and Multimode Memories.*, Phys. Rev. Lett., v. 98, 190503 (2007).

Quantum logic operations in $^{40}Ca^+$ and ^{43}Ca trapped-ion qubits

C. J. Ballance*, D. T. C. Allcock, N. M. Linke, T. P. Harty, L. Guidoni,
H. A. Janacek, D. P. L. Aude Craik, D. N. Stacey, A. M. Steane, and D. M. Lucas

Clarendon Laboratory, University of Oxford, Parks Road, OX1 3PU, Oxford, UK
**ballance@physics.ox.ac.uk*

We have successfully implemented a magnetic-field-insensitive qubit in the intermediate magnetic field (146G) in the ground state manifold of $^{43}Ca^+$ using an in-house designed and microfabricated surface ion trap. The trap incorporates integrated microwave waveguide resonators to drive the qubit transitions at 3.2 GHz. We intend to implement motional gates using the large gradient present in the evanescent field above the microwave resonators as recently demonstrated [1]. Preliminary results indicate that the trap has a heating rate amongst the lowest measured in a surface trap at room temperature, and that the qubit has a coherence time of order 10 s.

Secondly, we are aiming to implement a two-qubit gate using two different isotopes of calcium ($^{40}Ca^+$ and $^{43}Ca^+$) in a macroscopic linear Paul trap. The isotope shift (~ 1 GHz) allows us to individually address the two ions. Transitions are driven by two Raman lasers which manipulate both isotopes with low scattering error and high Rabi frequency [2]. We have achieved Raman sideband cooling close to the ground state ($\bar{n} < 0.1$) and simultaneous readout on both isotopes.

References

[1] C. Ospelkaus *et al.*, *Microwave quantum logic gates for trapped ions*, Nature **476**, 181 (2011).
[2] R. Ozeri *et al.*, *Errors in trapped-ion quantum gates due to spontaneous photon scattering*, Phys. Rev. A **75(4)**, pp. 1-14 (2007).

Quantumness of correlations and entanglement are different resources

T. Tufarelli, D. Girolami, R. Vasile, S. Bose, M. S. Kim, and G. Adesso[2,*]

1. QOLS, Blackett Laboratory, Imperial College London, London SW7 2BW, UK
2. School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK
3. Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
**gerardo.adesso@nottingham.ac.uk*

We investigate the resource power of general quantum correlations [1] (as measured by the geometric discord [2]) versus entanglement in a class of cat-like states ρ_{AB} of a two-level atom and a harmonic oscillator. The entanglement in these states can reach the maximum while the geometric discord is limited by the temperature T of the oscillator. We design two hybrid communication protocols that take advantage of either resource. One is a teleportation scheme where Bob teleports an unknown atomic state to Alice, via the shared resource ρ_{AB}: the fidelity reaches unity for any T. The second is a remote state preparation protocol where Alice can measure the atom to remotely prepare Bob's oscillator in some (known to Alice) state: here the fidelity is upper bounded by the geometric discord, decreasing with increasing T. We conclude that quantumness of correlations and entanglement are truly different resources, and different communication scenarios can exploit one ignoring the other, and vice versa.

References

[1] Z. Merali, *Quantum computing: The power of discord*, Nature **474**, 24 (2011).
[2] B. Dakić, C. Brukner, and V. Vedral, Phys. Rev. Lett. **105**, 190502 (2010).

Nonlocality of a cat state following non-Markovian evolutions

Jie Li[1], Gerard McKeown[1], Fernando L. Semião[2,*], and Mauro Paternostro[1]

1. Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queen's University, Belfast BT7 1NN, UK
2. Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, R. Santa Adélia 166, 09210-170 Santo André, São Paulo, Brazil
**fernando.semiao@ufabc.edu.br*

We study the time evolution of Bell-CHSH functions for a spin-oscillator cat-like state evolving according to two models for non-Markovian dynamics, and we find that the different facets of non- Markovianity affect nonlocality in different and non-obvious ways [1]. In the first model, Brownian motion is considered for the oscillator system and we find that it affects the non-local nature of a cat state in quite a significant way when the cut-off frequency of the Brownian bath is much smaller than the natural oscillation frequency of the oscillator, i.e. in the regime that would correspond to a strong non-Markovian limit. In this case, large-amplitude revival peaks are found, showing the kick-back mechanism that the memory-keeping environment can exert over the system. In the second model, we use a post-Markovian master equation for the spin part and we find that it is unable to induce a nonmonotonic decay of the Bell-CHSH function. Yet, such dynamics is nondivisible and as such it deviates from the prescriptions commonly accepted for Markovianity.

Reference

[1] J. Li, G. McKeown, F. L. Semião e M. Paternostro, *Non-Markovian effects on the nonlocality of a qubit-oscillator system*, Phys. Rev. A **85**, pp. 022116 (2012).

Modeling single photon production in RASE

Robin Stevenson*, Sarah Beavan, Morgan Hedges, Andre Carvalho,
Matt Sellars, and Joseph Hope

Research School of Physics and Engineering,
The Australian National University, Canberra, Australia
**Robin.Stevenson@anu.edu.au*

Rephased Amplified Spontaneous Emission (RASE) from an ensemble of rare-earth ions has been observed in experiment [1], however detector inefficiencies and noise on the signal have prevented non-classical correlations from being demonstrated. This work presents theoretical modelling of both Amplified Spontaneous Emission (ASE) from the ensemble when all ions are in the excited state, and the RASE rephasing process, once an emission has been detected and the population of the ensemble has been inverted. The optimal optical depth of the ion ensemble is found to maximise the production of single-photon states while minimising multi-photon production, and also to maximise the probability of a rephased photon being emitted. This will be used to chose an operating point for future RASE experiments. The emission profile of an ensemble prepared after a multi-photon detection is also calculated.

Reference

[1] S. Beavan, Photon-echo rephasing of spontaneous emission from and ensemble or rare-earth ions, PhD thesis, The Australian National University, January 2012.

The dimension of nonsignaling box

Keng-Shuo Wu

IAMS, Academia Sinica, No. 1, Sec. 4, Roosevelt road, Taipei, 10617, Taiwan
kengshuowu@ntu.edu.tw

It is demonstrated that genuine random numbers can be generated from a system consisting of two entangled atoms (ions) [1]. This nonlocal system can be characterized as a bipartite binary input and binary output box [2]. Due to the irreducible randomness intrinsic to a quantum system, the relationship between inputs and outputs is characterized by a conditional joint probability distribution $P(ab \mid xy)$, which is determined by the quantum state and measurement setups. Notably, toavoid superluminal (fast-than-light) communication, a nonlocal box does not allow signaling. Our work shows that one can use correlation functions to produce all the probability distribution of a nonsignaling box. As a result, the number of independent parameters (the dimension) of a nonsignaling box is the number of its correlation functions.

References

[1] S. Pironio, A. Acin, S. Massar, A. Boyer de la Giroday, D. N. Matsukevich, P. Maunz, S. Olmschenk, D. Hayes, L. Luo, T. A. Manning, and C. Monroe, *Random numbers certified by Bell's theorem*, Nature **464**, pp. 1021-1024 (2010).
[2] J. Barrett, N. Linden, S. Massar, S. Pironio, S. Popescu, and D. Roberts, *Nonlocal correlations as an information-theoretic resource*, Phys. Rev. A **71**, 022101 (2005).

Quantum computing with incoherent resources and quantum jumps

Marcelo F. Santos[1], Marcelo Terra Cunha[2,*], Rafael Chaves[3], and André R. R. Carvalho[4]

1. Departamento de Física, Universidade Federal de Minas Gerais, Belo Horizonte, CP 702, 30123-970, Brazil
2. Departamento de Matemática, Universidade Federal de Minas Gerais, Belo Horizonte, CP 702, 30123-970, Brazil
3. ICFO-Institut de Ciències Fotòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
4. Centre for Quantum Computation and Communication Technology, Department of Quantum Science, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 0200 Australia
**tcunha@mat.ufmg.br*

Spontaneous emission and the inelastic scattering of photons are two natural processes usually associated with decoherence and the reduction in the capacity to process quantum information. Here [1] we show that, when suitably detected, these photons are sufficient to build all the fundamental blocks needed to perform quantum computation in the emitting qubits while protecting them from deleterious dissipative effects. We exemplify this by showing how to efficiently prepare graph states for the implementation of measurement-based quantum computation.

Reference

[1] M. F. Santos, M. Terra Cunha, R. Chaves, and A. R. C. Carvalho, *Quantum Computing with Incoherent Resources and Quantum Jumps*, Phys. Rev. Lett. **108**, 170501 (2012).

Reversal of a strong quantum measurement by quantum error correction

Philipp Schindler, Julio T. Barreiro, Daniel Nigg, Matthias Brandl, Michael Chwalla[1,2], Thomas Monz, Markus Hennrich[1,*], and Rainer Blatt[1,2]

1. Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria
2. Institute for Quantum Optics and Quantum Information, A-6020 Innsbruck, Austria
**markus.hennrich@uibk.ac.at*

The strong measurement of a quantum state is a non-reversible process that projects the system onto the eigenstates. Therefore, it is generally not possible to reconstruct the state prior to the measurement. However, the measurement projection can also beregarded as a qubit error which can be rectified by quantum error correction techniques. We report on the experimental realization of such quantum measurement reversal in a system of trapped Calcium ions. We adapt the 3-qubit quantum error correction code presented in [1] which corrects for single qubit phase flips errors and is therefore ideally suited for the reversal of measurement projection of one of the three qubits. Here, the quantum information is encoded in an entangled logical qubit $\alpha|{+}{+}{+}\rangle + \beta|{-}{-}{-}\rangle$ of three physical qubits. The measurement projection of a single physical qubit onto $|0\rangle$ and $|1\rangle$ does not reveal any information on the state of the logical qubit, i. e. the quantum information is protected by entanglement. The error correction sequence finally rectifies phase errors that occurred during the measurement.

Reference

[1] P. Schindler, *et al.*, Experimental Repetitive Quantum Error Correction, Science **332**, 1059 (2011).

Nonlinear optics with double slow light pulses

Ying-Cheng Chen*, Chi-Ching Lin, Meng-Chang Wu, Bor-Wen Shiau, and Ya-Fen Hsiao

Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan
**chenyc@pub.iams.sinica.edu.tw*

We experimentally demonstrated a double slow light scheme (DSL) based on double electromagnetically induced transparency (EIT) in optically dense, cold cesium atoms [1]. The cross-Kerr nonlinearity between the two weak slow-light pulses is obtained through the asymmetric five-level M-type system formed by the two sets of EIT systems [2]. The group velocities of the two pulses are tuned to a matched condition to prolong the interaction time [3]. In the first DSL experiment to implement the cross-phase modulation, we have obtained a cross-phase shift of 10^{-6} radian per photon [1]. However, the nonlinear efficiency is still lower than that of four-level N-type system without DSL scheme [4] due to a linear loss in the switching EIT system in which a small two-photon detuning is introduced to obtain nonzero cross-Kerr nonlinearity. We have successfully demonstrated an improved DSL scheme in which a nonzero cross-Kerr exists even with both EIT systems on their two-photon resonance. We studied the nonlinear process of all optical switching and have overcome the N-type limit by a factor of 2.6. The nonlinear efficiency can be further improved by increasing the optical depth of the medium.

References
[1]B.-W. Shiau, M.-C. Wu, C.-C. Lin and Y.-C. Chen, Phys. Re. Lett. **106**, 193006 (2011).
[2] C. Ottaviani, S. Rebic', D. Vitali, and P. Tombesi, Eur. Phys. J. D **40**, 281 (2006).
[3] M. D. Lukin and A. Imamog)lu, Phys. Rev. Lett. **84**, 1419 (2000).
[4]S. E. Harris and L. V. Hau, Phys. Rev. Lett. **82**, 4611 (1999).

Optical diamond nanocavities for integrated quantum networks

Birgit Hausmann*, Yiwen Chu*, Brendan Shields[1], Nathalie de Leon[1], Michael Burek[2], Ruffin Evans[1], Matthew Markham[3], Alastair Stacey[3], Daniel Twitchen[3], Marko Lončar[2], and Mikhail Lukin[1]

1. Department of Physics, Harvard University, Cambridge, USA
2. School of Engineering and Applied Sciences, Harvard University, Cambridge, USA
3. Element Six Ltd, Kings Ride Park, Ascot SL5 8BP, UK
**lukin@physics.harvard.edu*

Nitrogen-Vacancy (NV) centers in diamond have emerged as a promising solid-state platform for quantum communication, quantum information processing [1], and metrology. Engineering the light-matter interaction between NV centers and nanophotonic devices can greatly enhance the performance of these systems. We demonstrate fabrication of diamond-based optical cavities containing and coupled to individual NV centers, with the potential for dramatic enhancement of the NV center's zero-phonon line via the Purcell effect. Localized modes having quality factors up to 6,000 have been achieved, resulting in a Purcell factor of 10. In addition, we investigate the properties of NV centers inside nanoscale structures and present novel techniques to ensure desirable spectral properties. These devices could enable strong coupling between the cavity field and NV centers, in addition to intriguing applications such as single photon transistors and quantum networks.

Reference
[1] I. Aharonovich, A. D. Greentree, and S. Prawer, "Diamond photonics", *Nature Photon.* **5**, pp. 397–405 (2011).

Coherent manipulation of a single hard x-ray photon

Wen-Te Liao*, Adriana Pálffy, and Christoph H. Keitel

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany
**wen-te.liao@mpi-hd.mpg.de*

Seeking for elegant ways of performing computations on the most compact scale is one of the crucial objectives in both fundamental physics and information technology. The photon as the flying qubit is anticipated to be the fastest information carrier and provide the most efficient computing. However, extending Moore's law to the future quantum photonic circuits must meet the bottleneck of the diffraction limit, e.g., few hundred nm for the optical region. The pioneering experiment [1] of incoherent photon storage were carried out with the wavelength of 0.86 Å and might overcome this size issue. Using this scheme, another novel idea [2] has also shown the potential of creating single-photon entanglement in the x-ray regime. Here we will demonstrate a new way of manipulating a single hard x-ray photon, including the coherent storage and the phase modulation of its wave packet [3]. We expect that such x-ray quantum optics schemes will help advancing quantum computation on very compact scales.

References

[1] Yu. V. Shvyd'ko, *et al.*, *Storage of Nuclear Excitation Energy through Magnetic Switching*, Phys. Rev. Lett. **77**, 3232 (1996).
[2] Adriana Pálffy, Christoph H. Keitel and Jörg Evers, *Single-Photon Entanglement in the keV Regime via Coherent Control of Nuclear Forward Scattering*, Phys. Rev. Lett. **103**, 017401 (2009).
[3] Wen-Te Liao, Adriana Pálffy and Christoph H. Keitel, *Coherent storage and phase modulation of single hard x-ray photons using nuclear excitons*, arXiv:1205.5503v1 (2012).

Photon localization in cold atoms: from Dicke to Anderson

L. Bellando[1], T. Bienaimé[1], J. Chabé[1], E. Akkermans[2], N. Piovella[3], and R. Kaiser[1]

1. Institut Non Linéaire de Nice, CNRS/Université Nice-Sophia-Antipolis, 06560 Valbonne, France
2. Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel
3. Dipartimento di Fisica, Università Degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy
**robin.kaiser @inln.cnrs.fr*

The quest for Anderson localization of waves is at the center of many experimental and theoretical activities. Cold atoms have emerged as interesting quantum system to study coherent transport properties of light. Initial experiments have established that dilute samples with large optical thickness allow studying weak localization of light. The goal of our research is to study coherent transport of photons in dilute and dense atomic samples. One important aspect is the quest of Anderson localization of light with cold atoms and its relation to Dicke super- or subradiance.

We present experimental and theoretical results [1-3], emphasizing the role of long range interactions between the atomic dipoles resulting in dominant global Dicke like synchronization over Anderson localization in coherent wave transport in resonant media.

References

[1] T. Bienaime, N. Piovella, R. Kaiser, Phys. Rev. Lett,108,123602 (2012).
[2] T. Bienaime *et al.*, Phys. Rev. Lett,104,183602 (2010).
[3] E. Akkermans, A. Gero, R. Kaiser, Phys. Rev. Lett,101,103602 (2008).

Non-classical statistics of strongly-interacting dark-state Rydberg polaritons

Shannon Whitlock*, Christoph Hofmann, Georg Günter, Hanna Schempp, Martin Robert-de-Saint-Vincent, and Matthias Weidemüller

Physikalisches Institut, Universität Heidelberg, Heidelberg Germany
**whitlock@physi.uni-heidelberg.de*

Interfacing light and matter at the quantum level is at the heart of modern atomic and optical physics and is a unifying theme of many diverse areas of research. A prototypical realization is electromagnetically induced transparency (EIT), whereby quantuminterference gives rise to long-lived hybrid states of atoms and photons called dark-state polaritons [1]. in a fully coherent and reversible way. Here we report the observation of strong interactions between dark-state polaritons in an ultracold atomic gas involving highly excited (Rydberg) states. By combining optical imaging with counting of individual Rydberg excitations we probe both aspects ofthis atom-light system. Extreme Rydberg-Rydberg interactions give rise to a polariton blockade, which is revealed by a strongly nonlinear optical response of the atomic gas. For our system the polaritons are almost entirely matter-like allowing us to directly measure the statistical distribution of polaritons in the gas. For increasing densities we observe a clear transition from Poissonian to sub-Poissonian statistics, indicating the emergence of spatial and temporal correlations between polaritons. These experiments, which can be thought of as Rydberg dressing of photons, show that it is possible to control the statistics of light fields, and could form the basis for new types of long-range interacting quantum fluids.

Reference

[1] M. Fleischhauer and M. D. Lukin, *Dark-State Polaritons in Electromagnetically Induced Transparency*, Phys. Rev. Lett. **84**, pp. 5094-5097 (2000).

Superradiant phase transition with ultracold atoms in optical cavity

D. Nagy*, G. Szirmai, and P. Domokos

Wigner Research Centre for Physics, Budapest, Hungary
**nagy.david@wigner.mta.hu*

We discuss the dispersive coupling of a Bose-Einstein condensate to the field of a high-*Q* optical cavity. The optical field mediates an infinite-range atom-atom interaction which can induce the self-organization of a homogeneous BEC into a periodically patterned distribution above a critical driving strength [1]. This self-organization effect can be identified with the superradiant quantum phase transition of the Dicke model, however in our system, the role of the internal atomic states are played by the motional states of the condensate [2]. The cavity photon loss limits the observation of the quantum phase transition in the ground state and for long times one observes a non-equilibrium phase transition in the steady state of the system. We show that the critical fluctuations survive in the steady state, however the critical exponents are different from those in the ground state, furthermore the atom-field entanglement is peaked but not divergent in the steady state [3].

References

[1] D. Nagy, G. Szirmai and P. Domokos, *Self-organization of a Bose-Einstein condensate in an optical cavity*, Eur. Phys. J D **48**, pp. 127-137 (2008).
[2] D. Nagy, G. Konya, G. Szirmai, and P. Domokos, *Dicke-Model Phase Transition in the Quantum Motion of a Bose-Einstein Condensate in an Optical Cavity*, Phys. Rev. Lett. **104**, 130401 (2010).
[3] D. Nagy, G. Szirmai and P. Domokos, *Critical exponent of a quantum-noise-driven phase transition: The open-system Dicke model*, Phys. Rev. A **84**, 043637 (2011).

Generating non-Gaussian states using collisions between Rydberg polaritons

Jovica Stanojevic[1,*], Valentina Parigi, Erwan Bimbard, Alexei Ourjoumtsev, Pierre Pillet, and Philippe Grangier

1. Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ Paris-Sud, 2 Avenue Fresnel, 91127 Palaiseau, France
2. Laboratoire Aimé Cotton, Bâtiment 505, Univ Paris-Sud, 91405 Orsay cedex, France
**jovica.stanojevic@u-psud.fr*

We investigate the deterministic generation of quantum states with negative Wigner functions which arise due to giant non-linearities originating from collisional interactions between Rydberg polaritons. The state resulting from the polariton interactions may be transferred with high fidelity into a photonic state, which can be analyzed using homodyne detection followed by quantum tomography. We obtain simple analytic expressions for the evolution of polaritonic states under the influence of Rydberg-Rydberg interactions. In addition to generating highly non-classical states of the light, this method can also provide a very sensitive probe of the physics of the collisions involving Rydberg states.

Reference
[1] J. Stanojevic *et al.*, arXiv:1203.6764.

Nonlinear optics with cold Rydberg gases

Sevilay Sevinçli* and Klaus Mølmer

Department of Physics and Astronomy, Aarhus University
8000 Aarhus C, Denmark
**sevincli@phys.au.dk*

Owing to the high sensitivity of Rydberg atoms to external fields and to interactions among themselves, ultracold Rydberg gases provide an ideal system for nonlinear optics. Here, we investigate interaction effects on the nonlinear process such as four-wave mixing (FWM) and Electromagnetically induced transparency (EIT). The combination of interacting Rydberg gases and this kind of quantum coherent process has recently attracted considerable theoretical and experimental interest, as it holds promise for realizing extremely large nonlinearities by exploiting the exaggerated interactions between Rydberg atoms. We present a classical many-body approach to investigate mechanisms behind optical nonlinearities arising from strong Rydberg-Rydberg interactions. Our method can describe large numbers of excited atoms, and, at the same time, properly account for strong correlations and many-body entanglement as well as dissipative processes.

Perspectives for laboratory implementation of the DLCZ protocol for quantum repeaters

Milrian S. Mendes and Daniel Felinto

Departamento de Física – Universidade Federal de Pernambuco, 50670-901 Recife, PE – Brazil
milrian@gmail.com, dfelinto@df.ufpe.br

We analyze the efficiency and scalability of the DLCZ protocol for quantum repeaters through experimentally accessible measures of entanglement for the system, taking into account crucial imperfections of the stored entangled states. We calculate the degradation of the final state of the quantum-repeater linear chain for increasing sizes of the chain, and characterize it by a lower bound on its concurrence and the ability to violate the CHSH inequality. The minimum purity of the initial state, required to succeed in the protocol as the size of the chain increases, is obtained. We also provide a more accurate estimate for the average time required to succeed in each step of the protocol. The minimum purity analysis and the new time estimates are then combined to trace the perspectives for implementation of the DLCZ protocol in present-day laboratory setups.

References
[1] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, "Long-distance quantum communication with atomic ensembles and linear optics", Nature 414, 413 (2001).
[2] M. S. Mendes and D. Felinto, "Perspectives for laboratory implementation of the Duan-Lukin-Cirac-Zoller protocol for quantum repeaters", Phys. Rev. A 84, 062303 (2011).

Feedback in a cavity QED system for control of quantum beats

A. D. Cimmarusti[1], B. D. Patterson[1], L. A. Orozco[1], P. Barberis-Blostein[2], and H. J. Carmichael[3]

1. Joint Quantum Institute, University of Maryland and NIST, College Park, Maryland, USA
2. IIMAS, Universidad Nacional Autonoma de México, México DF, México
3. Dept. of Physics, University of Auckland, Auckland, New Zealand
**lorozco@umd.edu*

Conditional measurements on the undriven mode of a two-mode cavity QED system prepare a coherent superposition of ground states that generate quantum beats [1]. The continuous drive of the system, through the phase interruptions from Rayleigh scattering, induces decoherence that manifests itself in a decrease of the amplitude and an increase of the frequency of the oscillations [2]. Our recent experiments implement a feedback mechanism to protect the quantum beat oscillation. We continuously drive the system until we detect a photon that heralds the presence of a coherent superposition. We then turn the drive off to let the superposition evolve in the dark, protecting it against decoherence. We later turn the drive back on to measure the amplitude and frequency of the beats. The amplitude can increase by more than fifty percent while the frequency returns to the unshifted value. Worksupported by NSF, CONACYT, and the Marsden Fund of RSNZ.

References
[1] D. G. Norris, L. A. Orozco, P. Barberis-Blostein, and H. J. Carmichael, *Phys. Rev. Lett.* **105**, 123602 (2010).
[2] D. G. Norris, A. D. Cimmarusti, L. A. Orozco, P. Barberis-Blostein, and H. J. Carmichael, *Phys. Rev. A* **85**, 021804 (2012)

A superradiant laser with <1 intracavity photon

James K. Thompson*, Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Dominic Meiser, and Murray J. Holland

JILA, NIST, and Dept. of Physics, University of Colorado, Boulder, Colorado
**jkt@jila.colorado.edu*

We will describe a recently demonstrated cold-atom Raman laser that operates deep into the superradiant or bad-cavity regime [1]. The system operates with <1 intracavity photon and with an effective excited state decay linewidth <1 Hz. This model system demonstrates key physics for future active optical clocks (similar to masers) that may achieve frequency linewidths approaching 1 mHz due to 3 to 5 orders of magnitude reduced sensitivity to thermal mirror noise. The measured linewidth of our model system demonstrates that the superradiant laser's frequency linewidth may be below the single particle dephasing and natural linewidths, greatly relaxing experimental requirements on atomic coherence. The light field's phase provides a continuous non-destructive measurement of the collective atomic phase with a precision that in-principle can be near the standard quantum limit. The possibilities for future hybrid active/passive atomic clocks will be discussed.

Reference

[1] Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Dominic Meiser, Murray J. Holland, and James K. Thompson, "A steady-state superradiant laser with less than one intracavity photon", Nature **484**, pp. 78-81 (2012).

Dissipative preparation of entangled steady states in cavity QED and ion traps

Florentin Reiter*, Michael J. Kastoryano, and Anders S. Sørensen

QUANTOP, Danish Quantum Optics Center and Niels Bohr Institute, 2100 Copenhagen, Denmark
**reiter@nbi.dk*

We propose various schemes for the dissipative preparation of a maximally entangled steady state of two atoms in an optical cavity. Harnessing the natural decay processes of spontaneous emission and cavity photon loss, we apply an effective operator formalism [1] to identify and engineer effective decay processes, which reach an entangled steady state of two atoms as the unique fixed point of the dissipative time evolution. For trapped ions we achieve the same result by using engineered spontaneous emission. We investigate various aspects which are crucial for the experimental implementation of our schemes in existing cavity QED and ion trap setups. Our study shows promising performance for present-day and future experimental systems, in particular a qualitative improvement in the scaling of the fidelity error as compared to unitary protocols for cavity QED [2].

References

[1] F. Reiter and A. S. Sørensen, *Effective operator formalism for open quantum systems*, Phys. Rev. A **85**, 032111 (2012).
[2] F. Reiter, M. J. Kastoryano, and A. S. Sørensen, *Driving two atoms in an optical cavity into an entangled steady state using engineered decay*, New J. Phys. **14**, 053022 (2012); M. J. Kastoryano, F. Reiter, and A. S. Sørensen, *Dissipative Preparation of Entanglement in Optical Cavities*, Phys. Rev. Lett. **106**, 090502 (2011).

Propagation of a light pulse in the EIT medium modified by the microwave field

J. Korociński[1,*], A. Raczyński[1], J. Zaremba[1], and S. Zielińska-Kaniasty[2]

1. Nicolaus Copernicus University, Toruń, Poland
2. University of Technology and Life Sciences, Bydgoszcz, Poland
**j.koro@fizyka.umk.pl*

A coherent preparation of an atomic medium by a laser light can lead to modifications of its optical properties characterized by the electric susceptibility. It is thus possible to influence a propagation of a light pulse in such a medium. The most important effect in this class is the Electromagnetically Induced Transparency (EIT) [1]. Recently a number of papers have been devoted to a realization and control of EIT in the closed loop configuration, especially in a Λ-type system with an additional microwave field coupling two lower states [2, 3]. The main topic of my work is to investigate the propagation of a probe pulse of a given shape and finite duration inside an atomic sample under EIT with the additional microwave field.

References

[1] S. E. Harris, Phys. Today **50**(7), 36 (1997),
[2] H. Li, V. A. Sautenkov, Y. V. Rostovtsev, G. R. Welch, P. R. Hemmer, M. O. Scully, "Electromagnetically induced transparency controlled by a microwave field," Physical Review A **80**, 023820 (2009),
[3] E. A. Wilson, N. B. Manson, C. Wei, Y. Li-Juan, "Perturbing an electromagnetically induced transparency in a Lambda system using a low-frequency driving field. Part I," Physical Review A **72**,063813 (2005),

Towards a loophole-free Bell test with atom-photon entanglement

Colin Teo[1,*], Jiří Minář[1], Marcelo F. Santos[2], Valerio Scarani[3],Daniel Cavalcanti[1],
Mateus Araújo, Marco T. Quintino, and Marcelo T. Cunha[4]

1. Centre for Quantum Technologies, National University of Singapore, Singapore
2. Departamento de Física, Universidade Federal de Minas Gerais, Caixa Postal 702, 30123-970 Belo Horizonte, MG, Brazil
3. Department of Physics, National University of Singapore, Singapore
4. Departamento de Matemática, Universidade Federal de Minas Gerais, Caixa Postal 702, 30123-970 Belo Horizonte, MG,Brazil
**colintzw@gmail.com*

Since the original Bell's idea a lot of different Bell tests have been performed, mostly using the means of quantum optics. Apart from their fundamental significance, the Bell tests are a very useful tool in the quantum information processing tasks, namely in the device independent scenarios. Necessary requirement to assess the validity of a Bell test is to close both the detection and locality loopholes, the goal with still missing experimental evidence. It was shown in [1, 2, 3], that a hybrid entangled state of a single atom and the coherent light field can violate the Bell inequality with moderate transmission and detection efficiencies. Here we present an experimental proposal realizing such a hybrid entangled states by means of cavity QED with a single atom. We show, that this state can be achieved using realistic experimental parameters available up-to-date yielding the CHSH violation of up to 2.25 and propagation distances of order of 100 meters for optical systems.

References

[1] D. Cavalcanti, *et. al.*, *Large Violation of Bell inequalities using both particle and wave measurements*, Phys. Rev. A **84**, 022105 (2011).
[2] M. Quintino, *et. al.*, *Maximal violations and efficiency requirements for Bell tests with photodetection and homodyne measurements*, J. Phys. A: Math. Theor. **45**, 215308 (2012).
[3] N. Sangouard, *et. al.*, *Loophole-free Bell test with one atom and less than one photon on average*, Phys. Rev. A **84**, 052122 (2011).

Salecker-Wigner-Peres clock and tunneling times for localized particles

Luiz A. Manzoni[1,*] and José T. Lunardi[2]

1. Physics Department, Concordia College, 901 8th St. S., Moorhead, MN 56562, USA
2. Grupo de Física Teórica e Modelagem Matemática, Departamento de Matemática e Estatística, Universidade Estadual de Ponta Grossa. Av. General Carlos Cavalcanti, 47481 84030-000, Ponta Grossa, PR, Brazil
**manzoni@cord.edu*

We address the longstanding problem of defining the time for a particle to tunnel through a potential using the Salecker-Wigner-Peres (SWP) quantum clock [1]. After a brief discussion the applicability of such clock to general potentials [2] and the role of the localizability of the tunneling particle [3], we argue for the need to perform a post-selection of the final state to obtain an average that can be interpreted as transmission (or reflection) time and obtain an expressionfor an average tunneling time valid for general localized potentials. The properties of this time scale are investigated both in the non-relativistic and relativistic scenarios – numerical results are presented for several potentials and, in particular,it is shown that this time scale does not exhibit the Hartman effect (nor its generalized version). Finally, the interpretation of the SWP clock and of the results obtained are discussed in the context of the weak measurement theory.

References

[1] H. Salecker and E. P. Wigner, *Phys. Rev.* **109**, 571 (1958); A. Peres, *Am. J. Phys.* **48**, 552 (1980).
[2] M. Calçada, J. T. Lunardi and L. A. Manzoni, *Phys. Rev. A* **79**, 012110 (2009).
[3] J. T. Lunardi, L. A. Manzoni and A. T. Nystrom, *Phys. Lett. A* **375**, 415 (2011).

Towards quantum Zeno dynamics with Rydberg atoms in a cavity

Bruno Peaudecerf[1,*], Théo Rybarczyk[1], Adrien Signoles[1], Saverio Pascazio[2], Paolo Facchi[2], Sébastien Gleyzes[1], Igor Dotsenko[1], Michel Brune[1], Jean-Michel Raimond[1], and Serge Haroche[1,3]

1. Laboratoire Kastler Brossel, CNRS/ENS/UPMC-Paris 6, 24 rue Lhomond, 75005 Paris, France
2. Dipartimento di Fisica and MECENAS, Università di Bari, I-70125, Bari, Italy
3. Collège de France, 11 place Marcellin Berthelot, 75005 Paris, France
**bruno.peaudecerf@ens.fr*

Quantum Zeno dynamics (QZD) generalizes the quantum Zeno effect in which repeated measurements inhibit the coherent evolution of a system [1]. In QZD, the measured observable has degenerate eigenspaces in which the system evolution is confined. We have proposed [2] an implementation of QZD for a field stored in a cavity and evolving under the action of a resonant classical source. Repeated interrogation of an atom coupled to the cavity restricts the field evolution to a subspace with a photon number lower or larger than a prescribed value. This dynamics generates interesting non-classical states and can be turned into phase space tweezers to prepare nearly arbitrary quantum superposition of coherent states. We present the principle of the method and the progresses toward its experimental implementation with slow circular Rydberg atoms in a high Q superconducting microwave cavity.

References

[1] J. Bernu *et al.*, Phys. Rev. Lett. **101**, 180402 (2008).
[2] J.-M. Raimond *et al.*, Phys. Rev. Lett. **105**, 213601 (2010).

Generation of intense cw radiation with high sub-Poissonian photon statistics in the cavity-QED microlaser

Younghoon Song[1], Wontaek Seo[2], Hyun-Gue Hong[2], and Kyungwon An[1,*]

1. Department of Physics and Astronomy, Seoul National University, Seoul, 151-747, Korea
2. Samsung Advanced Institute of Technology, Yongin, Gyeonggi-do, 446-712, Korea
**kwan@phya.snu.ac.kr*

The cavity-QED microlaser, a microscopic laser based on the cavity-QED principle, now finds applications in precision measurement, quantum information and ultralow noise communication owing to its intense cw outout with nonclassical photon statistics. The sub-Poissonian photon statistics in the microlaser originates from the active photon-number stabilization due to a decreasing gain function with the photon number. Since the previous observation of Mandel Q of -0.128, many efforts were made on further improvement in system stability and detection hardware. Supersonic atomic beam at a higher oven temperature and improved cavity locking reduced the fluctuations in the interaction time and the atom-cavity detuning, which led to the more enhanced photon-number stabilization. Furthermore, we fixed the defects in the detection system, which induced a distortion in Mandel Q measurement at high photon flux. As a result, we could observe Mandel Q of -0.48, which corresponds to about 4 times larger shot-noise reduction than the previous one.

Reference

[1] W. Choi, *et al.*, "Observation of sub-Poisson Photon Statistics in the Cavity-QED Microlaser," Phys. Rev. Lett. **96**, 093603 (2006).

Quantum correlated pulses from a synchronously pumped optical parametric oscillator

V. A. Averchenko[1,*], K. Hammerer[1], C. Fabre[2], N. Treps[2], and Yu. M. Golubev[3]

1. Institute for Theoretical Physics and Institute for Gravitational Physics,
Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany
2. Laboratoire Kastler Brossel, Universite Pierre et Marie Curie - Paris 6,
ENS, CNRS; 4 place Jussieu, 75252 Paris, France
3. St. Petersburg State University,
ul. Ul'yanovskaya, 1, Stary Petershof, 198504 St. Petersburg, Russia
**valentin.averchenko@aei.mpg.de*

Optical frequency comb with non-classical properties can be produced via parametric down-conversion of a pumping comb in a degenerate synchronously pumped optical parametric oscillator. In the time domain we developed a quantum theory of the oscillator that describes its operation both below and above oscillation threshold and gives clear insight into the character of quantum properties of an output signal comb being a train of pulses. Now we are thinking about application of a frequency comb and its non-classical counterpart for ultra-precise position sensing, particularly, in gravitational wave detectors. Here the fundamental limit on an accuracy of position determination (standard quantum limit) appears as interplay between time-arrival uncertainty of pulses and light back-action on a mechanical sub-system.

Towards ultracold fermions in a 2D honeycomb lattice

B. Deissler*, D. Hoffmann, W. Limmer, T. Lupfer, T. Paintner,
W. Schoch, B. Vogler, and J. Hecker Denschlag

Institut für Quantenmaterie, Universität Ulm, 89069 Ulm, Germany
**benjamin.deissler@uni-ulm.de*

We are setting up a new experiment with ultracold fermionic atoms in a two-dimensional honeycomb lattice to investigate intriguing phenomena which are either related to relativistic quantum physics (e.g. Zitterbewegung, Klein tunnelling) or to condensed matter physics (quantum criticality, quantum spin liquid). This system has the underlying geometry of graphene, but can be tuned and controlled in a much greater range. In the experiment, a degenerate Fermi gas of ^{6}Li will be created after laser cooling in a magneto-optical trap (MOT) and subsequent evaporative cooling in the vicinity of a Feshbach resonance in a strong optical dipole trap. The atoms will then be transferred optically into a glass cell, where they will be loaded into a two-dimensional honeycomb potential. We plan to use a site-resolved imaging technique in order to manipulate the particles and analyze their distribution in the lattice. We will show the experimental progress towards a degenerate Fermi gas.

Bosonic mixtures in a double-well trap: disorder-induced localization

Jun Qian* and Yuzhu Wang

Key Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics,
Chinese Academy of Sciences, Shanghai 201800, China
**jqian@siom.ac.cn*

We propose a simple model of bosonic mixtures in a double-well trap to investigate the disorder-induced collapse of the phase coherence which can cause the localization of major atoms. It is found that the number of impurity atoms randomly distributed in two subwells and the inter-species interaction play an important role in the correlation of the major atoms. It strikingly shows that the delocalization can even occur when intra-species and inter-species interactions are comparable, which exhibits a ‘twonegatives make a positive’ effect. We also calculate the dependence of the compressibility on the doping ratio and inter-species interaction, and the signature of Bose glass phase is predicted. In conclusion, our studies shows that even the simple two-site BH model can be useful to investigate more interesting physics in the disordered system of ultracold atoms.

An experiment for the investigation of artificial gauge fields in ultracold Ytterbium gases

A. Dareau*, M. Scholl, D. Döring, J. Beugnon, J. Dalibard, and F. Gerbier

Laboratoire Kastler Brossel, Ecole Normale Sup?rieure, CNRS, 24 rue Lhomond, 75005 Paris, France
**alexandre.dareau@lkb.ens.fr*

We will present an experiment aimed at the realisation of artificial gauge fields with ultracold neutral atoms in an optical lattice [1,2]. Combining intense gauge fields with strong on-site interactions should allow to explore atomic analogs of fractional quantum Hall systems. The atomic species Ytterbium combines the advantages of a large number of both bosonic and fermionic isotopes and a long lived metastable state ($^3P_0$, lifetime 16 s), and its level scheme favours the implementation of a two-dimensional optical lattice, where the ground and excited states arrange in spatially separated sublattices. Optical coupling of the two states enables tunneling between the sublattices, resulting in a geometric phase of the atomic wavefunction equivalent to the Aharonov-Bohm phase of a charged particle in a magnetic field. We will present the first results on cooling Ytterbium atoms in our apparatus and describe the experimental techniques to implement laser-induced gauge potentials.

References
[1] D. Jaksch and P. Zoller, *Creation of effective magnetic fields in optical lattices: the Hofstadter butterfly for cold neutral atoms*, New J. Phys. **5**, 56 (2003).
[2] F. Gerbier and J. Dalibard, *Gauge fields for ultracold atoms in optical superlattices*, New J. Phys. **12**, 033007 (2010).

Imaging and manipulating bilayer quantum gases

M. Eric Tai, Ruichao Ma, Philipp Preiss, Jonathan Simon, and Markus Greiner*

Department of Physics, Harvard University, Cambridge, MA 02138, USA
**greiner@physics.harvard.edu*

Single-atom/single-site resolved experiments with ultracold neutral atoms in optical lattices offer direct access to local observables and correlation functions in strongly-interacting many-body systems. Such quantum gas microscopes have thus far been limited to investigating purely two-dimensional systems. Here, we present a scheme for single-atom/single-site resolved readout of a bilayer degenerate gas. By engineering occupation-dependent transport between two tunnel-coupled planes, our system can be used to unambiguously identify atom numbers n = 0 to n = 3 per site ("beyond parity imaging"). We obtain the first single-site resolved images of the Mott insulator shell structure with up to three atoms per site and study the formation of doublon-hole pairs across a magnetic quantum phase transition. Our technique significantly improves the imaging capabilities of quantum gas microscopes and creates new possibilities for the simulation of bilayer condensed matter systems with ultracold atoms.

Nanoplasmonic optical lattices for ultracold atoms

M. Gullans[1,*], T. Tiecke[1], D. E. Chang[2], J. Feist[2], J. D. Thompson[1], J. I. Cirac[3], P. Zoller[4], and M. D. Lukin[1]

1. Department of Physics, Harvard University, Cambridge, MA 02138, USA
2. ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
3. Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
4. Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria
**mgullans@fas.harvard.edu*

Ultra-cold atoms in artificial potentials created by interfering light waves constitute a powerful tool to study strongly correlated many-body systems. However, the relevant length and energy scales are at present limited by an optical wavelength. We propose to use sub-wavelength confinement of light associated with near field of plasmonic systems to create a nanoscale optical lattice for ultracold atoms. Our approach combines the unique coherence properties of isolated atoms with the subwavelength manipulation and the strong light-matter interaction associated with nano-plasmonic systems. It allows one to considerably increase the energy scales in the realization of Hubbard models and to create effective long-range interactions in coherent and dissipative dynamics of atoms. As an example we demonstrated how these techniques can be used to prepare and study many-body states of AKLT type in the steady state of an optically driven system.

Anderson localization of Dirac fermions on a honeycomb lattice

Kean Loon Lee[1,*], Benoît Grémaud[1,2,3], Christian Miniatura[1,2,4], and Dominique Delande[3]

1. Centre for Quantum Technologies, National University of Singapore, Singapore
2. Department of Physics, National University of Singapore, Singapore
3. Laboratoire Kastler Brossel, Ecole normale supérieure, CNRS, UPMC, Paris, France
4. Institut Non Linéaire de Nice, UMR 7335, UNSA, CNRS, Valbone, France
**keanloon.lee@quantumlah.org*

We study the tight-binding model with uncorrelated diagonal disorder on a honeycomb lattice. We use three independent methods: recursive Green's function, self-consistent Born approximation and time-evolution of a Gaussian wave packet, to extract scattering mean free path ℓ_s, scattering mean free time τ, density of states ρ and localization length ξ. The three methods give excellent quantitative agreement of the single-particle properties (ℓ_s, τ, ρ). Furthermore, a finite-size analysis of ? reveals that the finite-size localization lengths of different lattices and different energies (including the charge neutrality point of a honeycomb lattice) can be described by the same single-parameter curve. However, the extracted numerical value of shows great deviation from the prediction of self-consist theory of localization. Our numerical results also show possible indication of weak localization corrections.

Mobile impurities in one-dimensional cold gases: subdiffusive, diffusive and ballistic regimes

A. Kantian[1,*], U. Schollwöck[2], and T. Giamarchi[1]

1. DPMC, Université de Genève, Quai Ernest Ansermet 24, 1211, Genève, Suisse
2. Center for NanoScience, University of Munich, Theresienstrasse 37, 80333 Munich, Germany
**Adrian.Kantian@unige.ch*

Advances in cold gases physics are beginning to enable experiments involving the direct manipulation and observation of single- or few-atom mobile impurities [1] within a many-body quantum system, a topic of longstanding interest for condensed matter theory, where it is related to studies of e.g. conductivity and the X-ray edge problem. Further progress in this direction is expected from the latest generation of experiments offering single-site addressability in optical lattices [2, 3] .

In light of these developments we study the dynamics of mobile impurities in 1D quantum liquids using a DMRG technique. We address the recently proposed subdiffusive regime of impurity motion [4], a class of excitations beyond those described by the standard Tomonaga-Luttinger theory. We study the conditions for observing this regime and its' crossover to the ballistic regime. We furthermore examine the possibilities to observe the intermediate diffusive motion of impurities in these systems.

References
[1] J. Catani, G. Lamporesi, D. Naik *et. al.*, PRA **85**, 023623 (2012).
[2] W. S. Bakr, J. I. Gillen, A. Peng *et. al.*, Nature **462**, 74 (2009).
[3] J. F. Sherson, C. Weitenberg, M. Endres *et. al.*, Nature **467**, 7311 (2010).
[4] M. B. Zvonarev, V. V. Cheianov, T. Giamarchi, PRL **99**, 110401 (2009).

Collisions involving nD + nD Rydberg states in a dipole trap

Jader Cabral*, Jorge K. Massayuki, Luis F. Gonçalvez, and Luis G. Marcassa

Laboratory of Atomic Interaction - IFSC, University of São Paulo, Brazil
**jscabral@ursa.ifsc.usp.br*

We have studied nD + nD multilevel pairwise interactions between Rydberg atoms in a magneto-optical trap, and our results have shown that the electric field plays an essential role in the interaction dynamic [1,2]. In this work, our goal is to study the nD + nD interaction in a higher density cold sample in a dipole trap. Therefore, we have loaded a QUEST trap for Rb using a CO_2 laser. The dipole laser beam is focused to a spot size ($1/e^2$) around 70 µm. For 75 W laser power, the QUEST depth is ~ 730µK and the density sample is arround $4x10^{11}$ atoms/cm^3. The nD Rydberg states are excited using a CW blue light (480nm) with 1MHz of linewidth. During the presentation we will show our first results on the nD + nD interactions in a CO_2 optical trap.

References
[1] J. S. Cabral *et al.,* "Effects of electric fields on ultracold Rydberg atom interactions", J. Phys. B: At. Mol. Opt. Phys. 44 (2011) 184007 (12pp).
[2] J. S. Cabral *et al., "*Manipulation of quantum state transfer in cold Rydberg atom collisions", New J. Phys. 12 09302(2010).

Controlled optical collisions in a metastable neon MOT

R. D. Glover, J. E. Calvert, D. E. Laban, and R. T. Sang*

Centre for Quantum Dynamics, Griffith University, Brisbane, Australia, 4111
**R.Sang@griffith.edu.au*

We present the results for controlled optical collisions of cold, metastable neon atoms in a magneto-optical trap [1]. The modification of the ionizing collision rate is demonstrated using a control laser tuned close to the $(3s)^3P_2$ to $(3s)^3D_3$ cooling transition. The measured ionization spectrum excludes resonances as a result of the formation of photoassociated molecules connected to the $\Omega = 5$ excited potential as predicted by Doery et. al [2]. Instead, we observe a broad unresolvable ionization spectrum that is well described by the established theory of Gallagher and Pritchard[3]. Depending on the frequency detuning of the control laser relative to the cooling transition, for a red frequency detuned laser beam we have measured up to 4 x enhancement of the ionization rate. In the case when the control laser us detuned to the blue of the cooling transition we observe optical shielding and a reduction in the ionization rate of up to a factor of 5. We will present the results of this investigation.

References
[1] R. D. Glover, J. E. Clavert, D. E. Laban and R. T. Sang, *J.Phys. B* **44**, 245202 (2011).
[2] M. R. Doery, E. J. D. Vredenbregt, J. G. C. Tempelaars, H. C. W. Beijerinck, B. J. Verhaar, *Phys. Rev. A* **57**, pp. 3603-3620 (1998).
[3] A. Gallagher and D. E. Pritchard, *Phys, Rev. Lett*. **63**, pp 957-960 (1989).

Radiative double-electron capture by bare nucleus with emission of one photon

E. A. Chernovskaya[1,*], O. Yu. Andreev[1], and L. N. Labzowsky[1,2]

1. Faculty of Physics, St. Petersburg State University, Uluanovskaya 1, 198504, Petergof, St. Petersburg, Russia
2. Petersburg Nuclear Physics Institute, 188300, Gatchina, St. Petersburg, Russia
**jkfizfak@rambler.ru*

Calculation of the cross-section for the process of double-electron capture by a bare nucleus with emission of a single photon is presented. The double-electron capture is evaluated within the framework of quantum electrodynamics. The line-profile approach is employed. Since the radiative double-electron capture is governed by the electron correlation, corrections to the interelectron interaction were calculated with high accuracy, partly to all orders of the perturbation theory. The calculations of the cross-section are presented not only for the experiments [1, 2, 3] as it was also shown in [4] but for new experiments F^{9+} + C and Cr^{24+} + He / N_2 ions. Also we investigate the dependence of the cross-section from the energy of incoming ion are presented.

References
[1] A. Warczak, M. Kucharski, Z. Stachura, H. Geissel, H. Irnich, T. Kandler, C. Kozhuharov, P. H. Mokler, G. Münzenberg, F. Nickel, *et al.*, Nucl. Instr. Meth. Phys. Res. B **98**, p. 303 (1995).
[2] G. Bednarz, D. Sierpowski, T. Söhlker, A. Warczak, H. Beyer, F. Bosch, A. Bräuning-Demian, H. Bräuning, X. Cai, A. Gumberidze, *et al.*, Nucl. Instr. Meth. Phys. Res. B 205, 573 (2003).
[3] A. Simon, A. Warczak, T. ElKafrawy, and J. A. Tanis, Phys. Rev. Lett. 104, 123001 (2010).
[4] E. A. Chernovskaya, O. Yu. Andreev, L. N. Labzowsky Phys. Rev. A **84**, 062515 (2011).

Micromotion in trapped atom-ion systems

Le Huy Nguyen[1,2,*], Amir Kalev[2], Murray Barrett[2], and Berthold-Georg Englert[2,3]

1. NUS Graduate School for Integrative Science and Engineering, Singapore
2. Centre for Quantum Technologies, Singapore
3. Department of Physics, National University of Singapore, Singapore
**g0801853@nus.edu.sg*

We examine the influence of the ion micromotion on the controlled collision of a trapped atom and a single trapped ion. Using the transformation of Cook *et. al.* we find that the micromotion can be represented by two periodically oscillating operators. In order to study their effect, we calculate (i) the coupling strengths of the micromotion operators by numerical integration and (ii) the quasienergies of the system by applying the Floquet formalism — a useful framework for studying periodic systems. It turns out that the micromotion is not negligible when the distance between the atom and the ion traps is shorter than a characteristic distance. Within this range the energy diagram of the system changes remarkably when the micromotion is taken into account, which leads to undesirable consequences for applications that are based on an adiabatic collision process of the trapped atom-ion system. We suggest a simple scheme for bypassing the micromotion effect in order to successfully implement a quantum controlled phase gate proposed previously, and create an atom-ion macromolecule. The methods presented here are not restricted to trapped atom-ion systems and can be readily applied to studying the micromotion effect in any system involving a single trapped ion.

Cooperative interactions in nanometre-thickness thermal Rb vapour

J. Keaveney[1,*], A. Sargsyan[2], I. G. Hughes[1], D. Sarkisyan[2], and C. S. Adams[1]

1. Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK
2. Institute for Physical Research, National Academy of Sciences - Ashtarak 2, 0203, Armenia
**james.keaveney@durham.ac.uk*

Similar to cavity QED, the reflection of the field by neighbouring dipoles in a dense medium gives rise to a cooperative enhancement of the atom-light interaction. Such cooperative effects manifest as a of the decay rate (super- or subradiance) and a shift of the resonance known as the cooperative Lamb shift. By tuning the atomic density and layer thickness of a nanometre-scale atomic vapour cell, we are able to move continuously from negligible to dominant dipole–dipole interactions, and experimentally measure these cooperative effects including the cooperative Lamb shift, in agreement with theoretical predictions of nearly 40 years ago [1,2]. Finally we report on recent results on the propagation of light in the cooperative limit where the effects of superradiance and slow or fast light are combined.

References

[1] J. Keaveney, A. Sargsyan, U. Krohn, I. G. Hughes, D. Sarkisyan and C. S. Adams, *Cooperative Lamb shift in an atomic vapor layer of nanometer thickness*, Phys. Rev. Lett. **108**, 173601 (2012); see also Physics **5**, 46 (2012).
[2] R. Friedberg, S. Hartmann and J. T. Manassah, *Frequency shifts in emission and absorption by resonant systems ot two-level atoms*, Phys. Rep. **7**, pp. 101-179 (1973).

Electron spin waves in atomic hydrogen gas

Kalle-Antti Suominen[1,*], Otto Vainio[1], Janne Ahokas[1], Sergey Sheludyakov[1], Denis Zvezdov[1,2], Simo Jaakkola[1], and Sergey Vasiliev[1]

1. Department of Physics and Astronomy, University of Turku, 20014 Turku, Finland
2. Kazan Federal University, 420008, 18 Kremlyovskaya St, Kazan, Russia
**Kalle-Antti.Suominen@utu.fi*

We present a high magnetic field study of electron spin waves in atomic hydrogen gas compressed to high densities of ~ 10^{18} cm^{-3} at temperatures 0.26 - 0.6 K [1]. We have observed a variety of spin wave modes caused by the collisionally induced identical spin rotation effect with strong dependence on the spatial profile of the polarizing magnetic field. We demonstrate confinement of these modes in regions of strong magnetic field and manipulate their spatial distribution by changing the position of the field maximum. At high enough densities a sharp and strong peak appears in the ESR spectrum, originating from the spin wave modes trapped in magnetic field maximum. This is accompanied by spontaneous coherence of the transversal magnetization, similar to that of the homogeneously precessing domain in liquid ^{3}He, where this can be interpreted as Bose-Einstein condensation of magnons [2].

References
[1] O. Vainio, J. Ahokas, S. Sheludyakov, D. Zvezdov, K.-A. Suominen, and S. Vasiliev, *Guiding and Trapping of Electron Spin Waves in Atomic Hydrogen Gas*, Phys. Rev. Lett **108**, pp. 185304 (2012) [5 pages].
[2] Yu. M. Bunkov, and G. E. Volovik, *Magnon Bose Einstein Condensation and Spin Superfluidity*, J. Phys. Condens. Matter **22**, pp. 164210 (2010) [5 pages].

Precision measurement of *s*-wave scattering lengths in ^{87}Rb

Mikhail Egorov[1,2], Bogdan Opanchuk[1], Peter Drummond[1], Brenton Hall[1], Peter Hannaford[1], and Andrei Sidorov[1,*]

1. Swinburne University of Technology, Melbourne, Australia
2. Monash University, Melbourne, Australia
**asidorov@swin.edu.au*

We use collective oscillations and trapped Ramsey interferometry of a two-component Bose-Einstein condensate of ^{87}Rb atoms (states $|1> \equiv |F = 1, m_F = -1>$ and $|2> \equiv |F = 2, m_F = 1>$) for the precision measurement of the interspecies scattering length a_{12} and the intraspecies scattering length a_{22}. We show that in a cigar-shaped trap the 3D dynamics of a component with a small relative population can be conveniently described by a 1D Schrödinger equation for an effective harmonic oscillator. The frequency of the collective oscillations is defined by the ratio a_{12}/a_{11} and is largely decoupled from the scattering length a_{22}, the total atom number and two-body loss terms. By fitting numerical simulations of the coupled Gross-Pitaevskii equations to the recorded temporal evolution of the axial width we obtain the value $a_{12} = 98.006(16)a_0$, Using Ramsey interferometry of the two-component condensate we measure the scattering length $a_{22} = 95.44(7)a_0$.

Reference
[1] M. Egorov, B. Opanchuk, P. Drummond, B. V. Hall, P. Hannaford and A. I. Sidorov, "Precision measurement of s-wave scattering lengths in a two-component Bose-Einstein condensate", Arxiv: 1204.1591 (2012).

Rb resonance spectroscopy in a random porous medium

S. Villalba[1], H. Failache[1], A. Laliotis[2,1], L. Lenci, S. Barreiro[1], and A. Lezama[1,*]

1. Instituto de Física, Universidad de la República, J.H. y Reissig 565, 11300, Montevideo, Uruguay
2. Laboratoire de Physique des Lasers UMR 7538 du CNRS, Université Paris-13, F-93430 Villetaneuse, France
**alezama@fing.edu.uy*

We have studied the transmission spectrum of Rb atomic vapor confined inside the intersticial cavities of a random porous medium. The medium, made of compacted ground pyrex glass, with approximately 50 μm mean grain size, fills one end of a closed cylindrical Rb vapor spectroscopic cell. The porous sample strongly diffuses light with a diffusion distance $D \lesssim 1$ mm. We detected laser light frequency scanned around the Rb D1 transitions that has traversed several millimeters of the porous sample. Using fast time-resolved detection, synchronized to a sudden change in laser intensity, we were able to identify the contribution to the transmitted light of photons being spontaneously emitted by the Rb atoms. For low atomic densities, the randomness of the photon trajectories in the sample results in an "integrating sphere" effect in which the re-emission of light almost cancels the atomic absorption. At large atomic densities, the contributions of absorption and spontaneous emission to the transmission present noticeable spectral differences. Also, as the atomic density is increased, the characteristic decay time of the spontaneously emitted photons increases and the fraction of absorbed energy being re-emitted decreases. We interpret these observations as due to the onset of photon trapping in connection with non-radiative decay in atom-wall collisions.

Casimir-Polder interaction between ultracold atoms and a carbon nanotube

Andreas Günther*, Philipp Schneeweiss, Michael Gierling, Peter Federsel, Thomas E. Judd, and József Fortágh*

CQ Center for Collective Quantum Phenomena and their Applications
Eberhard-Karls-Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
**a.guenther@uni-tuebingen.de*
**fortagh@uni-tuebingen.de*

Interfacing cold atom clouds and nanostructures, especially carbon nanotubes has been attracting large interest because the objects have similar atom numbers and masses. This enables both mechanical and electronic manipulation of solids by atoms and vice-versa. In our experiment, we bring ultracold atom clouds of rubidium into spatial overlap with a free standing carbon nanotube thus atoms are scattered on the tube. We observe the time dependent atom loss from thermal clouds and Bose-Einstein condensates, from which we derive the Casimir-Polder interaction potential [1]. We identify the scattering radius and the regimes of quantum mechanical scattering between rubidium atoms and the carbon nanotube. We report on the technique of "cold-atom scanning probe microscopy" [2] for imaging the topography of nanostructures and for ultrasensitive force measurements.

References

[1] P. Schneeweiss *et al.*, *Dispersion forces between ultracold atoms and a carbon nanotube*, in print.
[2] M. Gierling *et al.*, *Cold-atom scanning probe microscopy*, Nature Nanotechnology **6**, pp. 446-451 (2011).

Importance of correlation – polarization and PCI in Electron Impact single ionization of Xe atom

Prithvi Singh, Vinod Patidar, and G. Purohit*

Department of Physics, School of Engineering, Sir Padampat Singhania University, Bhatewar, Udaipur-313 601, India
**ghanshyam.purohit@spsu.ac.in, prithvipurohit@gmail.com*

The charged particle impact ionization studies of fundamental atomic and molecular systems have been of great interest since the early days of quantum mechanics. Extensive theoretical and experimental investigations have been carried out to understand the electron impact single ionization (i. e. (e, 2e) processes) of various targets (see [1] and references cited therein). Accurate cross sections for Xe atom target ionization by electron impact are very important for the understanding of the complex interactions involved in the plasma processes. We will report triple –differential cross section of Xe atoms for low energy (e, 2e) ionization at the incident electron energies ranging from 5 to 40 eV above the ionization threshold from coplanar to perpendicular plane geometries in the modified distorted wave Born approximation formalism. We will discuss the effect of target polarization and post collision interaction in coplanar as well as the perpendicular plane geometrical conditions. We will also compare the result of our calculation for Xe with the very recent measurements of Nixon *et al.* [2].

References

[1] G. Purohit, Prithvi Singh, Vinod Patidar, Y. Azuma, and K. K. Sud, Phys. Rev. A **85**, 022714 (2012).
[2] K. L. Nixon and A. J. Murray, Physical Review A **85**, 022716 (2012).

Influence of three-body interactions on Rb fine-structure transfer in inert buffer gases

Alina Gearba[1,2], Jerry Sell[1], Brian Patterson[1], Robert Lloyd[1], Jonathan Plyler[1], and Randy Knize[1]

1. Laser and Optics Research Center, US Air Force Academy, Colorado Springs, Colorado, USA
2. Department of Physics and Astronomy, University of Southern Mississippi, Hattiesburg, Mississippi, USA
**alina.gearba@usm.edu and jerry.sell@usafa.edu*

We will present measurements of the mixing rates and cross sections for collisional excitation transfer between the $5P_{1/2}$ and $5P_{3/2}$ states of rubidium in the presence of inert buffer gases. Selected pulses from a high repetition rate, mode-locked ultrafast laser are used to excite either Rb state with the fluorescence due to collisional excitation transfer observed by time-correlated single-photon counting. The measured mixing rates exhibit a linear dependence on the buffer gas density at low pressures, but include a significant quadratic component at buffer gases densities greater than 1 atm. We attribute this quadratic component to three-body interactions which alter the collisional transfer cross section by reducing the fine-structure splitting between Rb 5P levels. We examine this effect for a range of buffer gas temperatures and pressures[1] along with mixtures such as Rb-He-Ar.

Reference

[1] M. A. Gearba, J. F. Sell, B. M. Patterson, R. Lloyd, J. Plyler and R. J. Knize, "Temperature dependence of Rb 5P fine-structure transfer induced by ^{4}He collisions", Opt. Lett. **37**, pp. 1637-1639 (2012).

Investigation of temperature behaviour of alkane- and alkene-based anti-relaxation coatings of caesium vapour cells

Oleg Yu. Tretiak[1,*] and Mikhail V. Balabas[1,2]

1. Faculty of Physics, St. Petersburg State University, 198504 St. Petersburg, Russian Federation
2. S. I. Vavilov State Optical Institute, 199034 St. Petersburg, Russian Federation
**otretiak@genphys.ru*

The temperature (294° K < T < 340° K) dependence of the longitudinal (T_1), transverse (T_2) relaxations times and atoms absorption rate were experimentally investigated for two cells with alkane- and alkene-based coatings. The $T_1(T)$ and $T_2(T)$ were measured by Franzens "relaxation in the dark" and double radio-optical resonance method accordingly. Both cells showed a growth of T_1 to a certain temperature (T = 332° K for alkane- and T = 298° K for alkene-based coatings), after which the T_1 decreased rapidly. T_2 has a monotone decrease for alkane- and does not change for alkene-based coatings in a whole measured temperature range. The concentration of Cs atoms in bulb was monitored by measuring of transmitted through the cell light intensity after quick closing of the valve between bulb and Cs reservoir for studying of atoms absorption rates [1]. Different character temperature dependence of slow and fast components of characteristic time for alkane- and alkene-based coating were found.

Reference

[1] M. V. Balabas, O. Yu. Tretiak *Investigation of temperature dependence of kinetics of irreversible caesium atoms leaving from vapour phase to anti-relaxation coating.*, Technical Physics **9**, pp. 75-82 (2012).

Inelastic confinement-induced resonances in low-dimensional quantum systems

Simon Sala*, Philipp-Immanuel Schneider, and Alejandro Saenz

Institut für Physik, Humboldt-Universität zu Berlin, Germany
**ssala@physik.hu-berlin.de*

Ultracold atomic systems of reduced dimensionality show intriguing phenomena like fermionization of bosons in the Tonks-Girardeau gas or confinement-induced resonances (CIRs) which allow for a manipulation of the interaction strength by varying the trap geometry. Here, a theoretical model is presented describing inelastic confinement-induced resonances which appear in addition to the regular (elastic) ones and were observed in the recent loss experiment of Haller et al. in terms of particle losses [1]. These resonances originate from possible molecule formation due to the coupling of center-of-mass and relative motion. The model is verified by ab initio calculations and predicts the resonance positions in 1D as well as in 2D confinement in agreement with the experiment. This resolves the contradiction of the experimental observations to previous theoretical predictions.

Reference

[1] E. Haller et al., *Phys. Rev. Lett.* **104**, 153203 (2010).

On the photoionization cross section in Rydberg states: possible evidence of Cooper minina

Claudia Dums Schmidt[1,3], Ricardo Antonio De Simone Zanon[1,3], Carlos Eduardo Fellows[2,3], and André Luiz de Oliveira[1,3,*]

1. Departamento de Física, Universidade do Estado de Santa Catarina,Joinville, Santa Catarina, Brazil
2. Instituto de Física, Universidade Federal Fluminense, Niterói, Rio de Janeiro, Brazil
3. Instituto Nacional de Óptica e Fotônica, INOF/CNPq, Brazil
**andre.oliveira@udesc.br*

Rydberg atoms have as one of their characteristic the high principal quantum number. Their large dimensions imply in a large dipole moment, which allows one to use them for studies of atomic interactions with electromagnetic fields, including processes of photoionization. The increasing attention given to the investigation of photoionization cross sections of these highly excited atoms, is due to its importance to several areas like Atomic and Molecular Physics, Astrophysics, Plasma Physics, among others. Based on the model proposed by Aymar and co-workers [1] we studied the photoionization cross sections of alkali atoms, expanding the previous analysis to $n \geq 44$. Furthermore, the photoionization cross sections for the ground state are well known (both theoretically and experimentally [1], but the same is not true for the excited states. We performed an analysis of the behaviour of radial wave functions depending on the photoelectron energies and by analysing them we have alsoperformed a study of the Cooper minima.

Reference

[1] M. Aymar et. al., J. Phys. B , **17**, 993 (1984).

Study of Rydberg EIT in ultracold atoms across the BEC transition

Anushyam Mohan[2], Zhi Wei Wang[2], Fong En Oon[2], Mirco Siercke[1,2,*], and Rainer Dumke[1,2]

1. Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore
2. Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore
**cqtmirco@nus.edu.sg*

Electromagnetically induced transparency (EIT) involving Rydberg states [1] has become the subject of interest in cold atom experiments due to a wealth of possible applications ranging from quantum computing to mediated photon-photon interactions [2]. We study the behaviour of Rydberg EIT in an ensemble of ultracold ^{87}Rb as it is cooled through the transition to Bose-Einstein condensation. We observe the familiar dipole blockade as a function of atom density and find good agreement between the experimental scaling of the blockade radius and theory. No discontinuous behaviour is observed as the gas is cooled through the BEC phase transition. By realizing Rydberg EIT in condensates we will be capable of studying the strong nonlinear interactions introduced by the effect in ultracold, dense atomic gases.

References

[1] J. D. Pritchard, D. Maxwell, A. Gauguet, K. J. Weatherill, M. P. A. Jones, and C. S. Adams, *Cooperative Atom-Light Interaction in a Blockaded Rydberg Ensemble*, Phys. Rev. Lett. **105**, 193603 (2010).
[2] Alexey V. Gorshkov, Johannes Otterbach, Michael Fleischhauer, Thomas Pohl, and Mikhail D. Lukin, *Photon-Photon Interactions via Rydberg Blockade*, Phys. Rev. Lett. **107**, 133602 (2011).

Chaos-induced enhancement in electron recombination in highly charged ions

V. A. Dzuba[1], V. V. Flambaum[1,*], C. Harabati[1], and G. F. Gribakin[2]

1. School of Physics, University of New South Wales, Sydney 2052, Australia
2. Department of Applied Mathematics and Theoretical Physics, Queen's University, Belfast BT7 1NN, Northern Ireland, UK
**v.flambaum@unsw.edu.au*

We developed a statistical theory for the resonant multi-electron recombination based on properties of chaotic eigenstates [1]. Level density of many-body states exponentially increases with the number of excited electrons. When the residual electron-electron interaction exceeds the interval between these levels, the eigenstates become "chaotic" superposition of a large number of Hartree-Fock determinant basis states. This situation takes place in some rare-earth atoms and majority of multiply-charged ions excited by the electron recombination. We derived a formula for the resonant multi-electron recombination via di-electron doorway states leading to such compound resonances and performed numerical calculations for the electron recombination with tungsten ions W^{q+}, q = 17 – 24. A recent experiment [2] showed that the electron recombination of tungsten ion W^{20+} exceeds the theoretical direct recombination by three order of magnitude. Our calculations agree with this experimental result.

References
[1] V. V. Flambaum, A. A. Gribakina, G. F. Gribakin, and C. Harabati, *Electron recombination with multicharged ions via chaotic many-electron states*, Phys. Rev. A **60**, pp. 012713-7 (2002).
[2] S. Schippers *et al.*, *Dielectronic recombination of xenonlike tungsten ions*, Phys. Rev. A **83**, pp. 012711-6 (2011). 457 (1999).

Ultracold atom-ion collisions in mixed dimensions

S. Srinivasan*, A. Simoni, and J. M. Launay

Institut de Physique de Rennes, UMR-CNRS 6251 and Université de Rennes 1, 35042 Rennes, France
**srihari.srinivasan@univ-rennes1.fr*

We study ultracold collisions in a model 1D system formed by a free atom and a trapped ion. This model describes motion in a waveguide with spacing between transverse modes much larger than both the ion trap level spacing and the collision energy. We consider a zero-range atom-ion interaction, appropriate to model the effect of the interatomic potential in loose traps. We investigate two situations: static harmonic trapping and time dependent rf-trapping (Paul trap) of the ion.

The static case is numerically treated using two approaches. The integral equation of scattering is solved by a spectral method adapted to treat the kernel singularity. The close coupled form of the Schrödinger equation is solved using a log-derivative propagation approach to obtain directly the S-matrix. Coupling between center of mass and relative motion results in nontrivial resonance effects. The molecular states associated to the resonances are identified based on numerical bound level calculations. In the case of time-dependent rf-trapping, we use the Floquet theorem to convert the problem to a time independent formulation. The sparse linear system resulting from a high order finite element representation of the time-independent Hamiltonian issolved using available computer packages. We investigate the energy exchange between atom and ion, assessing the influence of the ion micromotion on the collision process. Our model could be applied to interpret results of current atom-ion experiments (1,2).

References
[1] S. Schmid, A. Härter, and J. H. Denschlag, *Phys. Rev. Lett.* **105**, 133202 (2010).
[2] C. Zipkes, S. Palzer, C. Sias, and M. Köhl, *Nature* **464**, 388 (2010).

Identification and non-destructive state detection of molecular ions

Kevin Sheridan, Nicolas Seymour-Smith, Amy Gardner, and Matthias Keller

Molecular Physics Laboratory, University of Sussex, Falmer, UK
**kts20@sussex.ac.uk*

Cold molecules have a multitude of applications ranging from high resolution spectroscopy and tests of fundamental theories to cold chemistry and, potentially, quantum information processing. Prerequisite for these applications is the cooling of the molecule's motion and its non-invasive identification. Futhermore, the internal state of the molecule needs to be prepared and non-destructively detected.

We have developed a novel technique to measure the average charge-to-mass ratio of trapped ions with high precision through broadband excitation of the ions' centre-of-mass mode motion and subsequent detection of the Doppler induced fluorescence modulation [1]. Chemical reactions between neutral molecules/atoms and trapped molecular ions can be investigated using this method by analysing the fluorescence of atomic ions which are trapped alongside the molecular ions. Due to the precision of this method, reaction rates and branching ratios can be measured even with large ion crystals (up to 100 ions).

The non-destructive state detection of trapped molecules is still beyond current experiments. Employing state selective laser induced dipole forces, we aim to detect the internal state of molecular ions by mapping the state information onto the ions' motion.

Reference

[1] Kevin Sheridan and Matthias Keller, *Weighing of trapped ion crystals and its applicaitons*, New J. Phys. **13**, 123002 (2011).

Vibrational quantum defect coupled to improved LeRoy-Bernstein formula for a precise analysis of photoassociation spectroscopy

Haikel Jelassi[1,*] and Laurence Pruvost[2]

1. National Centre for Nuclear Sciences and Technologies, 2020 Sidi Thabet, Tunis, Tunisia
2. Laboratoire Aimé Cotton, CNRS/Université Paris-Sud, Orsay, France
**haikel.jelassi@cnstn.rnrt.tn*

Laser photoassociation (PA) of cold atoms creates excited, weakly-bound molecules, which are key intermediates in the most of schemes that allow the formation of cold molecules in the ground state. For that reason the spectroscopy of these weakly bound molecules is one of the tools to know, not only the energy position of the levels but also if it exists their mixings with neighboring levels. Indeed, the mixings determine the wavefunction shapes, especially at short internuclear distance, and thus the Franck-Condon factors required for molecule formation. We show that, for an accurate analysis of the PA spectroscopy data, the LeRoy-Bernstein formula has to be improved [1]. Furthermore we show that the use of vibrational quantum defects and of Lu-Fano graphs provide efficient tools to determine and measure the couplings [2, 3, 4].

References

[1] H. Jelassi, B. Viaris de Lesegno, and L. Pruvost, Phys. Rev. A **77**, 062515 (2008).
[2] H. Jelassi, B. Viaris de Lesegno, and L. Pruvost, Phys. Rev. A **73**, 032501 (2006).
[3] H. Jelassi, B. Viaris de Lesegno, L. Pruvost, M. Pichler, and W. C. Stwalley, Phys. Rev. A **78**, 022503 (2008).
[4] L. Pruvost and H. Jelassi, J. Phys. B: At. Mol. Opt. Phys. **43**, 125301 (2010).

A study of cold ion-polar molecule reactions between sympathetically cooled molecular ions and slow polar molecules

Kunihiro Okada[1,*], Takahiro Furukawa[1], Masanari Ichikawa[1], Michiharu Wada[2], and Hans A. Schuessler[3]

1. Department of Physics, Sophia University, Tokyo, Japan
2. Nishina Center for Accelerator-Based Science, RIKEN, Saitama, Japan
3. Department of Physics, Texas A&M University, Texas, USA
**okada-k@sophia.ac.jp*

Cold ion-polar molecule reactions play important roles in the synthesis of intersteller molecules [1]. Even though the chemical reactions in dark interstellar clouds occur at very low temperatures, most of the reaction-rate constants in the astronomical database were measured at room temperature. Here we have developed a setup to directly measure cold ion-polar molecule reactions. We extended the experiment in Ref. [2] to the rate measurement between sympathetically cooled molecular ions and velocity-selected slow polar molecules. In fact we have successfully determined the reaction rate of $N_2H^+ + CH_3CN \rightarrow CH_3CNH^+ + N_2$ at very low temperatures. The results and a discussion of this research will be presented.

References
[1] V. Wakelam *et al.*, “Reaction Networks for Interstellar Chemical Modeling: Improvements and Challenges”, Space Sci. Rev. **156**, pp. 13-72 (2010).
[2] S. Willitsch *et al.*, “Cold Reactive Collisions between Laser-Cooled Ions and Velocity-Selected Neutral Molecules”, Phys. Rev. Lett. **100**, 043203 (2008).

Ultralong-range Rydberg molecules

Robert Löw*, Johannes Nipper, Jonathan Balewski, Alexander Krupp, and Tilman Pfau

Physikalisches Intitut, Universität Stuttgart, Germany
**r.loew@physik.uni-stuttgart.de*

We report on our recent experiments exploring ultralong-range Rydberg molecules. These unusual bound states between Rydberg atoms and ground state atoms feature novel binding mechanisms based on low energy electron scattering as well as internal quantum reflection at a shape resonance of electron-atom scattering [1]. Besides the binding energies of dimer and trimer states, further properties are studied in high resolution spectra in the high density regime. This extends from density dependent lifetime measurements to experiments in electric fields that reveal a molecular Stark effect due to a permanent electric dipole moment of the molecules [2].

References
[1] V. Bendkowsky, et.al., “Rydberg trimers and excited dimers bound by internal quantum reflection”, Phys. Rev. Lett. **105**, 16 (2010).
[2] W. Li, et.al., “A homonuclear molecule with a permanent electric dipole moment”, Science 334, 1110 (2011).

Hyperfine structure of RbCs excited molecules

Romain Vexiau*, Olivier Dulieu, Mireille Aymar, Nadia Bouloufa,
and Anne Crubellier[1]

Laboratoire Aimé Cotton, CNRS, Université Paris-Sud XI, Orsay, France
**romain.vexiau@u-psud.fr*

Unlike ground state alkali-metal diatomics, very little is known about the hyperfine structure of excited electronic states. We present a preliminary analysis of the expected hyperfine structure of the rovibrational levels of the RbCs excited electronic states correlated to the lowest $^2S + {}^2P$ limit, based on an asymptotic model for the hyperfine hamiltonian. We set up potential curves built on long-range atom-atom interaction connected to short-range ab initio results obtained in our group. The hyperfine structure strongly depends on the projection of the total angular momentum of the molecule, and on the sum of projections of the total angular momentum of the separated atoms.

Theory of mixed-field orientation for linear molecules: loss of adiabaticity

Juan J. Omiste[1,2,]* and Rosario González-Férez[1,2]

1. Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Spain
2. Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, Spain
**omiste@ugr.es*

We present a theoretical study of the mixed-field-orientation experiments of linear molecules, where a strong degree of orientation is obtained by means of a long linearly polarized laser pulse and a weak electric field [1]. We solve the corresponding time-dependent Schrödinger equation in the rigid rotor approximation, taking into account the time profile and the spatial distribution of the alignment pulse. Our non-adiabatic model reproduces the experimental observations for the OCS molecule [2]. We show that the adiabaticity of the mixed-field orientation depends on the avoided crossings that the states suffer and on the formation on the quasidegenate doublets in the pendular regime. For the first time, we show that the mixed field orientation is, in general, non-adiabatic being mandatory a time-dependent description of this process, and redefine the meaning of adiabatic conditions in these experiments [2].

References

[1] D. Dimitrovski *et al.*, *Ionization of oriented carbonyl sulfide molecules by intense circularly polarized laser pulses*, Phys. Rev. A, **83**, 023405 (2011).
[2] J. H. Nielsen *et al.*, *Making the best of mixed-field orientation of polar molecules: A recipe for achieving adiabatic dynamics in an electrostatic field combined with laser pulses*, arXiv:1204.2685 (Accepted in Physical Review Letters 2012).

Towards a Bose-Einstein condensate of ground-state molecules in an optical lattice

Katharina Lauber[1,*], Johann G. Danzl[1], Manfred J. Mark[1], Benjamin Rutschmann[1], Elmar Haller[2], and Hanns-Christoph Nägerl[1]

1. Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria
2. Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria
**Katharina.Lauber@uibk.ac.at*

Ultracold molecules trapped in an optical lattice at high density and prepared in their lowest internal quantum state are an ideal starting point for fundamental studies in physics and chemistry, ranging from novel quantum gas experiments and cold controlled chemistry to quantum information and quantum simulation.

In our experiment, we create ultracold and dense samples of molecules in their internal ground state in an optical lattice. We load a Bose-Einstein condensate of Cs atoms into the optical lattice potential and drive the superfluid-to-Mott-insulator transition under conditions that maximize double-site occupancy and efficiently create weakly bound Cs dimer molecules on a Feshbach resonance. These are subsequently transferred to a specific hyperfine sublevel of the rovibronic ground state by a coherent optical 4-photon process with the Stimulated Raman Adiabatic Passage (STIRAP) technique while each molecule is trapped in the motional ground state of an individual optical lattice well. We have implemented a series of technical improvements for optimized transfer efficiency and now aim at producing Bose-Einstein condensates of ground-state molecules by adiabatically removing the optical lattice potential.

Statistical evaluation of ultracold molecular fraction rate

Tomotake Yamakoshi[1,*], Chen Zhang[2], Chris H. Greene[2], and Shinichi Watanabe[1]

1. Department of Engineering Science,University of Electro-Communications, Tokyo, Japan
2. Department of Physics and JILA, University of Colorado, Boulder, USA
**t-yamakoshi@power1.pc.uec.ac.jp*

In recent years, various ultracold molecule production experiments have been carried out. Molecules are formed via a field ramp through a Fano-Feshbach resonance (FFR). They are subsequently transferred to the rovibrational ground state by STIRAP with very high efficiency. In this scenario, the final molecule conversion rate is restricted by the FFR fractional conversion. We study the FFR molecular fractional conversion rate using a Monte Carlo simulation based on the stochastic phase space sampling (SPSS) model[1]. The key idea of SPSS is that the phase space volume of atomic pairs does not change during an adiabatic magnetic sweep. We have applied this method to Fermi-Fermi, Bose-Bose, and Bose-Fermi cases, and have compared our SPSS result with that of the equilibrium theory[2]. We have identified some differences between results of the two approaches, especially in ultracold regions that have not yet been experimentally realized.

References
[1] E. Hodby *et al.*, “Production Efficiency of Ultracold Feshbach Molecules in Bosonic and Fermionic Systems”, Phys. Rev. Lett. **94**, 120402 (2005).
[2] S. Watabe and T. Nikuni, “Conversion efficiencies of heteronuclear Feshbach molecules”, Phys. Rev. A **77**, 013616 (2008).

Ro-vibrational cooling of molecules. Towards Sisyphus cooling of molecules

I. Manai, R. Horchani, G. Xu, M. Hamamda, H. Lignier*, D. Comparat, and P. Pillet

Laboratoire Aimé Cotton, CNRS/Université Paris-Sud, Orsay, France
**hans.lignier@u-psud.fr*

One of the greatest challenges of modern physical chemistry is to push forward the limits of electromagnetic or laser techniques to probe or manipulate molecules at low temperatures where molecular interactions are dominated by pure quantum phenomena. Following our pioneer work [1] we present our recent development concerning the rotational and vibrational cooling of the formed molecules: we are now able to transfer Cs_2 molecules into a single ro-vibrational level (including v = 0, J = 0) of the singlet ground electronic state. Combined with Sisyphus cooling, this method is probably able to produce a large sample of molecules at sub-mK temperature. The principle of Sisyphus cooling of molecules can be described in three steps: 1) removing kinetic energy through a motion in an external potential, 2) dissipative process preventing the reverse motion, 3) repetition of the “one-way” (or ”single photon”) process by bringing back the molecules to the initial state.

Reference

[1] M. Viteau, A. Chotia, M. Allegrini,N. Bouloufa, O. Dulieu, D. Comparat, P. Pillet, “Optical pumping and vibrational cooling of molecules”, *Science* **321** 232 (2008).

The spectroscopy and MOT for neutral mercury atoms

Hongli Liu[1], Shiqi Yin[1], Jun Qian[1], Zhen Xu[1,2], Tao Hong[1,3], and Yuzhu Wang[1,*]

1. Key Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
2. LNE-SYRTE, Observatoire de Paris, 61 Avenue de l’Observatoire, 75014 Paris, France
3. Center for Macroscopic Quantum Phenomena, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China
**yzwang@mail.shcnc.ac.cn*

Due to less blackbody radiation shifts, mercury atoms are regarded as one of the best candidates for optical lattice clock [1]. Here we report our recent progress towards laser cooling and trapping of mercury atoms for the ultracold sample ofoptical lattice clock. Several spectroscopies, including saturated absorption spectroscopy (SAS), DAVLL spectroscopy and frequency modulation (FM) spectroscopy, were investigated for the frequency discrimination and stabilization of the $^1S_0$-$^3P_1$ UV cooling laser. The ultra-high vacuum system of 3×10^{-9} Torr was designed and installed with the mercury source cooled by multi-stage-TEC. The ^{202}Hg atoms were trapped in the MOT, with the folded configuration by one beam cooling laser [2], and 2×10^6 atoms were detected by fluorescence method.

References

[1] M. Petersen *et al.*, *Doppler-Free Spectroscopy of the $^1S_0$-$^3P_0$ Optical Clock Transition in Laser-Cooled Fermionic Isotopes of Neutral Mercury*, Phys. Rev. Lett. **101**, 183004 (2008).

[2] H. Hachisu *et al.*, *Trapping of Neutral Mercury Atoms and Prospects for Optical Lattice Clocks*, Phys. Rev. Lett. **100**, 053001 (2008).

Transfer cold atoms from the time-averaged orbiting potential to an optical dipole trap

Weilun Hung, Hao-Yl Xiao, and Ite A. Yu*

Department of Physics and Frontier Research Center on Fundamental and Applied Sciences of Matters, National Tsing Hua University, Hsinchu 30013, Taiwan
**yu@phys.nthu.edu.tw*

We constructed an optical dipole trap (ODT) for rubidium-87 atoms with a 5W multimode Nd:YAG fiber laser. The beam waist of the focused laser beam is approximately 22 μm and the ODT has a trap depth of about 290 μK. The atoms were first cooled and compressed in the time-averaged orbiting potential trap (TOP) by ramping down the rotating magnetic field amplitude. At the end of the process, there were 4×10^7 atoms with a peak density above 1×10^{11} cm^{-3} and a temperature below 60 μK in the TOP. These atoms were transferred from the TOP to the ODT. We will report the studies of transfer efficiency and the temperature and lifetime of the trapped atoms in the ODT.

Preparing well-defined atom-number states in the evanescent field of an optical nanofibre

Tara Hennessy* and Thomas Busch

University College Cork, Ireland
OIST - Okinawa Institute of Science and Technology, Japan
thennessy@phys.ucc.ie

We present a scheme where the evanescent field around a sub-wavelength diameter tapered optical nanofibre is combined with an optical lattice. We show that when the fibre is aligned perpendicularly to the transverse plane of a two-dimensional optical lattice, the evanescent field around the fibre can be used to create a time-dependent potential which melts the lattice potential locally. We first describe the disturbance of the lattice due to scattering of the lattice beams on the fibre and then show how the attractive van der Waals potential close to the surface can be compensated by a repulsive blue-detuned evanescent field. This scheme allows access to a regime in which a small number of atoms can be locally addressed without disturbing the rest of the lattice. If the environment around the fibre is given by a Mott-Insulator state, the melting of the lattice transfers a well-defined number of atoms into the fibre potential. The resulting state is therefore an atom-number state and can be used for applications in quantum information. We also investigate another application of our system; using the fibre as a way of measuring the fidelity of the Mott Insulator state. By considering spontaneous emission of the atoms trapped in the lattice into the guided modes of the fibre as it passes close by, it is possible to determine whether specific sites are occupied or unoccupied.

Reference

[1] arXiv:1112.0899v2 (Accepted for publication in Physical Review A.).

High-optical-depth cold cesium gases for quantum optics experiments

Ya-Fen Hsiao*, Chi-Ching Lin, and Ying-Cheng Chen

Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan
**yafen.hsiao@gmail.com*

Many quantum optics experiments can benefit from cold atomic media with high optical depths, such as low-light-level nonlinear optics [1,2], high efficiency and capacity quantum memory [3,4], high-generation-rate photon pairs [5], and simulating quantum many-body physics with strongly-interacting photons [6]. We have combined the techniques of two-dimensional magneto-optical trap (MOT), dark and compressed MOT, and optical pumping to routinely obtain cold atomic samples with optical depths of ~200 for the $F=3 \rightarrow F=4$ transition of cesium D_2 line. Attempts to achieve even high optical depths are underway and the results will be presented.

References
[1] M. D. Lukin and A. Imamoğlu, Phys. Rev. Lett. **84**, 1419 (2000).
[2] A. André, M. Bajcsy, A. S. Zibrov, and M. D. Lukin, Phys. Rev. Lett. **94**, 063902 (2005).
[3] A. V. Gorshkov, A. André, M. Fleischhauer, A. S. Sørensen, and M. D. Lukin, Phys. Rev. Lett. **98**, 123601 (2007).
[4] J. Nunn, K. Reim, K. C. Lee, V. O. Lorenz, B. J. Sussman, I. A. Walmsley, Phys. Rev. Lett. **101**, 260502 (2008).
[5] Pavel Kolchin, Phys. Rev. A **75**, 033814 (2007).
[6] D. E. Chang, V. Gritsev, G. Morigi, V. Vuletić, M. D. Lukin and E. A. Demler, Nat. Phys. **4**, 884 (2008).

Integrated magneto-optical traps on a chip using micro-fabricated gratings

J. P. Cotter[1], C. C. Nshii[2], M. Vangeleyn[2], P. F. Griffin[2], C. N. Ironside[3], P. See[4], A. G. Sinclair[4], E. A. Hinds[1], E. Riis[2], and A. S. Arnold[2]

1. Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BW, UK
2. Department of Physics, University of Strathclyde, SUPA, 107 Rottenrow, Glasgow, G4 0NG, UK
3. Room 622, Rankine Building, School of Engineering, University of Glasgow, Glasgow G12 8LT, UK
4. National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

We have integrated magneto-optical traps (MOTs) into an atom chip which is able to cool and trap ~ 10^7 atoms directly from a thermal background of ^{87}Rb. Diffraction gratings are used to manipulate the light from a single input laser to create the beams required for a MOT[1]. The gratings are etched into the surface of a silicon wafer by either electron beam, or photo-lithography making them simple to fabricate and integrate into other atom chip architectures. Unlike previously integrated cold atom sources on a chip [2] the atoms now sit above the surface where they can be easily imaged, manipulated and transferred into other on-chip potentials. These devices significantly simplify the initial capturing of atoms, representing substantial progress towards fully integrated atomic physics experiments and devices. They also offer a simple way to integrate many atom sources on a single device.

References
[1] M. Vangeleyn *et. al.*, *Laser cooling with a single laser beam and a planar diffractor*, Opt. Lett. **35** 3453 (2010).
[2] S. Pollock *et. al.*, *Integrated magneto-optical traps on a chip using silicon pyramid structures*, Opt. Express **17**, 14109 (2009).

High-performance apparatus for simultaneously laser cooling of ^{87}Rb and ^{6}Li

Nozomi Ohtsubo*, Ikoma Daisuke, Takatoshi Aoki, and Yoshio Torii

Institute of Physics, The University of Tokyo, Japan
**ohtsubo@photon.c.u-tokyo.ac.jp*

The RbLi molecule is a promising candidate for exploring novel quantum phases of ultracold molecules owing to the relatively large electric dipole moment (4.2 Debye). We developed an apparatus for simultaneous laser cooling of ^{87}Rb and ^{6}Li for the purpose of creating fermionic RbLi molecules. We exploited separate Zeeman slowers for each species, which were attached to a stainless-steel chamber kept at ultra-high vacuum ($<10^{-11}$ Torr). The capture velocities for Rb and ^{6}Li are 300 m/s and 800 m/s, respectively. We performed Doppler-free polarization spectroscopy of Li in a heat-pipe oven for laser frequency stabilization. We found that the Ar buffer gas enhances the polarization signal, which is explained by a simple model considering velocity-changing collisions [1]. We could simultaneously collect 10^9 Rb atoms and 10^8 Li atoms in a magneto-optical trap. We also developed magnetic coils which offer a uniform magnetic field of about 1100 G for producing Feshbach molecules.

Reference

[1] Nozomi Ohtsubo, Takatoshi Aoki, and Yoshio Torii. "Buffer gas-assisted polarization spectroscopy of ^{6}Li", to appear in Opt. Lett. (arXiv:1204.2363).

Tuneable microwave sidebands by optical injection in diode lasers

Chris I. Laidler and Stefan Eriksson

Department of Physics, Swansea University, Singleton Park, SA2 8PP Swansea, UK

Optical injection in diode lasers can produce frequency tuneable sidebands[1]. We show that by carefully tailoring the frequency and intensity of the injection laser relative to the free running laser we can create narrow sidebands suitable for atomic physics experiments. We observe a frequency tuning range which exceeds the modulation bandwidth of the free running laser. Our detection bandwidth limits this measurement to a range of about 20 GHz, but the tuning range is predicted to be as wide as the longitudinal mode spacing of the diode laser[2] which can be of the order of 100 GHz. The sideband intensity can also be controlled by the injection. The output of a laser with this injection can be used to simultaneously address two transitions in common alkalis or small heteronuclear molecules. We demonstrate the frequency stability of the sidebands by magneto-optical trapping of rubidium using light from the injected laser only[3]. We propose further applicationsof the sideband technique.

References

[1] S.-C. Chan and J.-M. Liu, IEEE J. Sel. Top. Quantum Electron. **10**, p. 1025 (2004).
[2] S.-C. Chan, S.-K. Hwang and J.-M. Liu, Opt. Express **15**, p. 14921 (2007).
[3] C. I. Laidler and S. Eriksson, EPL **96**, p. 53001 (2011).

Isotope shifts of natural Sr^+ measured by laser fluorescence in sympathetically cooled Coulomb crystal

B. Dubost, R. Dubessy, B. Szymanski, S. Guibal, J.-P. Likforman, and L. Guidoni*

Université Paris–Diderot, Sorbonne Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162 CNRS, F-75205 Paris, France
**luca.guidoni@univ-paris-diderot.fr*

We measured by laser spectroscopy the isotope shifts between natural even-isotopes of strontium ions for both the $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ (violet) and the $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ (infrared) optical transitions. The fluorescence spectra have been obtained by simultaneous measurements on a two-species Coulomb crystal in a linear Paul trap containing $\sim 10^4$ laser-cooled Sr^+ ions. The isotope shifts are extracted from the experimental spectra by fitting the data with the solution of the optical Bloch equations describing a three-level atom in interaction with two laser beams. This technique allowed us to increase the precision with respect to previously reported data. The results for the $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ transition are $\nu_{88} - \nu_{84} = +378(3)$ MHz and $\nu_{88} - \nu_{86} = +170(2)$ MHz. In the case of the unexplored $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ transition we find $\nu_{88} - \nu_{84} = +822(6)$ MHz and $\nu_{88} - \nu_{86} = +400(2)$ MHz. These results provide more data to a stringent test for theoretical calculations of the isotope shifts of alkali-metal-like atoms [1].

Reference

[1] See for example: W. E. Lybarger, J. C. Berengut, and J. Chiaverini, *Precision measurement of the* $5^2\,S_{1/2} - 4^2\,D_{5/2}$ *quadrupole transition isotope shift between* $^{88}Sr^+$ *and* $^{86}Sr^+$, Phys. Rev. A **83**, 052509 (2011).

Injecting, extracting, and velocity filtering neutral atoms in a ring dipole trap

Yu. Loiko[1,2], V. Ahufinger[1], R. Menchon-Enrich[1], G. Birkl[3], and J. Mompart[1,*]

1. Departament de Física, Universitat Autònoma de Barcelona, Bellaterra, Spain
2. Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
3. Institut für Angewandte Physik, Technische Universitätt Darmstadt, Darmstadt, Germany
**jordi.mompart@uab.cat*

Ring traps for cold-atom physics can be foreseen as the low-energy counterpart of circular accelerators in high-energy physics. In this regard, we discuss here a coherent technique to inject, extract, and velocity filter neutral atoms in a ring dipole trap coupled to two additional dipole waveguides, by extending our previous work [1] to waveguides. By adiabatically following a particular transverse energy eigenstate of the system, the transverse spatial dark state, the proposed technique is shown to allow for an efficient and robust velocity dependent atomic population transfer between the ring and the input/output waveguide. We have derived analytical conditions for the adiabatic passage as a function of the atomic velocity along the input waveguide as well as on the initial population distribution among the transverse vibrational states. The performance of our proposal has been checked by numerical integration of the corresponding 2D Schrödinger equation with state of-the-art parameter values for a ring dipole trap with Rubidium atoms.

Reference

[1] Yu. Loiko, V. Ahufinger, R. Corbalán, G. Birkl, and J. Mompart, "Filtering of matter-wave vibrational states via spatial adiabatic passage", Phys. Rev. A **83**, pp. 033629(1)-033629(7) (2011).

Magnetic traps for cold atoms based on circular superconducting micro-structures

Bo Zhang

School of Science, Wuhan University of Technology, 122 Ruoshi Road, 430070 Wuhan, China
zhangbo2011@whut.edu.cn

We design magnetic traps for neutral atoms with the fields generated by supercurrents imprinted in type-II superconducting disks and rings. We simulate the current density distributions in these superconducting structures under different loading fields bymeans of the critical state method [1] and compute the resulting external magnetic fields with Biot-Savart theorem. The spatial inhomogeneous magnetic fields can be used to trap cold atoms with or without additional bias fields. Versatile supercurrent-patterns can be written in the superconducting disks and rings by programmable loading fields, which may lead to variable trapping potentials. We analyze in detail the quadrupole traps, self-sufficient traps and ring traps generated by the supercurrents written in the superconducting disks and rings. The absent of the transport currents and bias fields may reduce the noise from the power source. The ease of creating the ring traps and the low noise for trapping atoms make the circular superconducting structures attractive for atom chip interferometers.

Reference

[1] E. Brandt, *Thin superconductors in a perpendicular magnetic ac field. II. circular disk*, Phys. Rev. B **50**, pp. 4034-4050 (1994).

Laser cleaning and background-free detection in microfabricated ion traps

N. M. Linke[1,*], D. T. C. Allcock[1], L. Guidoni[2], C. J. Ballance[1], T. P. Harty[1], H. A. Janacek[1], D. P. L. Aude Craik[1], D. N. Stacey[1], A. M. Steane[1], and D. M. Lucas[1]

1. Clarendon Laboratory, University of Oxford, Parks Road, OX1 3PU, Oxford, UK
2. Université Paris Diderot, Paris, France
**linke@physics.ox.ac.uk*

We present recent work on laser cleaning of a microfabricated surface ion-trap. A particular problem in such traps is heating of the ion by electric field noise, which scales as $\sim d^{-4}$ with ion-surface distance d. Pulses from a 355nm frequency-tripled Nd:YAG laser were used to ablate surface adsorbates which reduced the heating rate by a factor of ~ 2, and changed its frequency dependence. This was the first experimental demonstration of in-situ reduction of an ion trap heating rate [1].

We also describe a Doppler cooling and detection scheme for ions with low-lying D levels which suppresses scattered laser light background (count rate 1 s^{-1}), while retaining a high fluorescence signal (29000s^{-1}) [2]. This scheme is useful for experiments where ions are trapped near surfaces.

Finally, we present data characterizing a three-dimensional microstructured gold-on-alumina ion trap. The chip has a cross-shaped trapping region with four individual trap arms connected by a central junction.

References

[1] D. T. C. Allcock *et al.*, *Reduction of heating rate in a microfabricated ion trap by pulsed-laser cleaning*, New J. Phys. **13** 123023 (2011).
[2] N. M. Linke *et al.*, *Background-free detection of trapped ions*, Appl. Phys. B **0946-2171** 1 (2012).

New developments in high power narrow linewidth fiber amplifiers for atomic physics

Peyman Ahmadi*, Jianwu Ding, Chiachi Wang, and Imtiaz Majid

Nufern, 7 Airport Park Road, East Granby, CT 06026, USA
**contact: pahmadi@nufern.com*

We present an overview of the recent progress in the narrow linewidth, high power fiber amplifiers, including progress on single frequency fibers operating at wavelengths outside the common 1064nm wavelength and at high power levels. Such high power sources can be utilized for efficient loading of Far-Off-Resonant-Traps (FORT) from MOT. Excellent beam quality, low noise and robust all-fiber designs that do not need realignment during the lifetime of the device are some of advantageous of fiber based sources. Examples of the latest results to be presented include, development of high power fiber amplifiers operating at output powers of ~ 1 kW, achieved through phase modulation of single frequency fiber sources to overcome SBS limitations. The latest results on GHz linewidth sources amplified to kW power levels will be presented along with novel architectures such as a remote amplifier head that simplify the use of the technology.

The adoption of active polarization control technology has enabled non-PM fiber amplifiers to operate with 17dB PER, eliminating the need for expensive PM components in the fiber amplifier chain. The use of Tm-doped fiber lasers and amplifiers at wavelengths around 2000nm will be presented including high power wavelength tuning results and high power single frequency amplification. Frequency doubling of narrow linewidth fiber sources is an attractive method to generate new wavelengths that are of interest for AMO community. Results of simple external frequency doubling using commercially available PPLN material for creating 532 (nm) with output power > 10 (W) will be presented.

An experimental setup for implementing graph states with Rydberg atoms

A. Kowalczyk[1,*], C. W. Mansell[1], C. MacCormick[1], S. Bergamini[1,**], and I. Beterov[2]

1. Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, MK6 7AA, UK
2. Institute of Semiconductor Physics, Lavrentyeva Avenue 13, 630090 Novosibirsk, Russia
**a.kowalczykr@open.ac.uk, **s.bergamini@open.ac.uk*

Utracold, neutral atoms are a potentially scalable platform to physically implement quantum information processing schemes. We have identified a specific experimental set-up as being especially well-suited to the implementation of the “one-way” model of quantum computation. The set-up includes a high numerical aperture lens and a spatial light modulator to create tightly focussed optical dipole traps that can be arbitrarily placed within the two-dimensional focal plane of the lens. For our particular case, a tetrahedral MOT design is particularly appealing, as it requires limited optical access whilst using low power coils for the quadrupole magnetic field. We present a special case of 4-beam MOT operating at very acute angle, which allows to cool atoms to temperatures of order 40μK. Atoms are then loaded into our tightly focused dipole trap. Ultracold atoms loaded into these traps can be laser-excited to Rydberg states that have strong, long-range, controllable interactions. The controllability of these interactions and the controllability of the geometry of the traps give us a highly versatile set-up to investigate the creation of multiparticle entangled states, including the “graph states” that are the starting point of the one-way model of quantum computation.

Bose-Einstein condensation of ytterbium for quantum information and simulation

Florian Schäfer[1,*], Pablo C. Pastor[1,2], Giacomo Cappellini[1], Jacopo Catani[1,2],
Marco Mancini[1,2], Guido Pagano[1,3], Massimo Inguscio[1,2], and Leonardo Fallani[1]

1. LENS and Dipartimento di Fisica ed Astronomia - Università di Firenze, 50019 Sesto Fiorentino (FI), Italy
2. INO-CNR, Sezione Sesto Fiorentino, 50019 Sesto Fiorentino (FI), Italy
3. SNS - Scuola Normale Superiore, 56126 Pisa, Italy
**schaefer@lens.unifi.it*

We report on the progress of the new experiment for cooling and trapping of atomic Ytterbium at LENS, University of Florence. The current setup includes a thermal Ytterbium atomic beam source, a Zeeman slower operating on the $^1S_0 - {}^1P_1$ transition, and a chamber for the MOT (using the $^1S_0 - {}^3P_1$ transition) with an in-vacuum optical Fabry-Pérot cavity to implement a FORT trap. We have achieved a BEC of bosonic ^{174}Yb in a crossed dipole trap and are currently working with the fermionic ($I = 5/2$) ^{173}Yb species. The goal is to load the ultra-cold atoms into a single layer, 2D optical lattice. There quantum simulations will be performed and the atoms will be manipulated individually to implement quantum computing operations. The ultra-narrow clock transition $^1S_0 - {}^3P_0$ will serve as an important tool for high-fidelity state manipulation and an appropriate laser system is developed and presented. Readout will be done via single site imaging by a high resolution objective lens.

An integrated fiber-trap for ion-photon quantum interface

Hiroki Takahashi[1,2,*], Andrew Riley-Watson[1], Alex Wilson[1], Matthias Keller[1],
and Wolfgang Lange[1]

1. University of Sussex, Falmer, Brighton, East Sussex, UK
2. PRESTO, Japan Science and Technology Agency, Tokyo, Japan
**ht74@sussex.ac.uk*

The controlled emission and absorption of single photons is an important enabling technology in the fields of quantum communication, cryptography and computing. We have realized a novel photonic system that tightly integrates optical fibers and a state-of-art ion trap [1]. The optical fibers not only work as photonic channels but their metallic jackets also provide a trapping electric field for the ion. This allows us to bring the fibers to within approximately 300 μm of the trapped ionwithout disturbing the trapping field. With a single cold ion trapped between the end facets of the two fibers, we are able to efficiently collect the ion's fluorescence using no further optics. Strong photon anti-bunching is observed in both the fluorescence from continuous excitation of the ion, and from pulsed excitation, where we are able to generate a pulse train of single photons with a defined temporal shape. The scheme can be extended to implement a coherent ion-photon interface through strong coupling cavity QED.

Reference

[1] A. Wilson, H. Takahashi, A. Riley-Watson, F. Orucevic, P. Blythe, A. Mortensen, D. R. Crick, N. Seymour-Smith, E. Brama, M. Keller, and W. Lange, *Fiber-coupled single ion as an efficient quantum light source*, *arXiv:1101.5877*.

Anderson localization of molecules in quasi-periodic optical lattices

Giuliano Orso* and Gabriel Dufour

Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot, Paris, France
**giuliano.orso@univ-paris-diderot.fr*

We investigate the formation of molecules made of two interacting atoms moving in a one dimensional bichromatic optical lattice. We derive the quantum phase diagram for Anderson localization of molecules as a function of interaction and the strength of the external potential. We show that the localization transition has fingerprints in the quasi-momentum distribution of molecules. When single particle states show multi-fractal behavior, the binding energy of molecules is found to exhibit an anomalous scaling exponent as a function of the interaction strength.

Reference

[1] G. Dufour and G. Orso, work in preparation.

Calculation of bound states of anisotropic potentials for the Schrödinger equation in two dimensions

Alexander Pikovski*

Institut für theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany
**pikovski@itp.uni-hannover.de*

Bound states of the Schrödinger equation in two dimensions for anisotropic potentials $\lambda V(\vec{r})$ are considered, where λ is a dimensionless coupling strength. Simon [1] studied shallow bound states with energies $E \to 0$ and couplings $\lambda \to 0$. Here, the methods of Ref. [1] are used to obtain exact integral equations for the energies and wavefunctions, for any energy and any coupling strength λ. The equations contain some freedom of choice which can be used to improve convergence. The expressions simplify if $V(\vec{r})$ has some symmetry. In the isotropic case, this reduces to what was obtained using the Jost function formalism [2]. Practical applications of the formulas for the calculation of bound-state energies are discussed.

References

[1] B. Simon, *The bound state of weakly coupled Schrödinger operators in one and two dimensions*, Annals of Physics **97**, 279 (1976).
[2] M. Klawunn, A. Pikovski, L. Santos, *Two-dimensional scattering and bound states of polar molecules in bilayers*, Phys. Rev. A **82**, 044701 (2010).

Pairing in a few-fermion system with attractive interactions

Gerhard Zürn[1,2,*], Thomas Lompe[1,2,3], Andre Wenz[1,2], Vincent Klinkhamer[1,2],
Andrea Bergschneider[1,2], Simon Murmann[1,2], and Selim Jochim[1,2,3]

1. Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Germany
2. Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
3. ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
**gerhard.zuern@mpi-hd.mpg.de*

We have studied few-particle systems consisting of one to six fermionic atoms in two different spin states in a 1D harmonic potential. We tune the strength of the attractive interaction between the particles using a Feshbach resonance and probe the systemby deforming the trapping potential and observing the tunneling of particles out of the trap. We find that the timescale of the tunneling process increases as a function of interaction strength. For even particle numbers we observe a tunneling behavior which deviates from uncorrelated single particle tunneling indicating the existence of pair correlations in the system. From the tunneling timescales of the systems we infer the binding energies for different particle numbers which show a strong odd-even effect, similar to the one observed in nuclei.

Pseudospin Hubbard model on the honeycomb lattice: a path-integral approach in the strong-coupling regime

F. G. Ribeiro[1,2,*] and M. D. Coutinho-Filho[1]

1. Laboratório de Física Teórica e Computacional, Departamento de Física, UFPE, Recife, Brazil
2. Laboratório de Física, Núcleo de Tecnologia, Centro Acadêmico do Agreste, UFPE, Caruaru, Brazil
**fgr@df.ufpe.br*

Quantum MC simulations for correlated electrons on a honeycomb lattice (graphene's lattice) [1] showed the presence of a quantum spin liquid phase between the usual semi-metal phase and an antiferromagnetically ordered Mott insulator phase, i.e., for intermediate strength interactions. Also, it was argued that in graphene the "electron's pseudospin" corresponds to a real angular momentum [2]. In this scenario, we present a path-integral approach for the pseudospin Hubbard model on the honeycomb lattice in the strong-coupling regime, in which case we show that the degrees of freedom of the Lagrangian density of the model exhibit pseudospin-charge separation. In this context, the Hamiltonian associated with the charge degrees of freedom is exactly diagonalized. Further, by means of a perturbative analysis we compute the Lagrangian density, and, at half-filling, we derive the action of the O(4) nonlinear σ-model with a topological Hopf term.

References

[1] Z. Y. Meng, T. C. Lang, F. F. Assaad and A. Muramatsu., *Quantum spin liquid emerging in two-dimensional correlated Dirac fermions*, Nature **464**, pp. 847-852 (2010).
[2] M. Mecklenburg and B. C. Regan, *Spin and the Honeycomb lattice: Lessons from Graphene*, Phy. Rev. Lett. **106**, pp. 116803-116807 (2011).

Borromean window for H_2^+ with screened Coulomb potentials

Sabyasachi Kar[1] and Y. K. Ho[2,*]

1. Center for Theoretical Atomic and Molecular Physics, The Academy of Fundamental and Interdisciplinary Sciences, Harbin Institute of Technology, Harbin 150080, P. R. China
2. Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan 106
**ykho@pub.iams.sinica.edu.tw*

Search for Borromean states for few-body quantum systems has gained considerable attention in recent years [1]. For an *N*-body system, a bound state is called Borromean state if there is no path to build it via a series of stable states by adding the constituents one by one. The Borromean binding is intimately related to two other fascinating phenomena, viz. Efimov effects and Thomas collapse. Borromean systems have also appeared in other areas such as nuclear physics, molecular physics, chemical physics and DNA. In this study, we are interested to search Borromean windows for the H_2^+ ions. With abundances of the H_2^+ ions in interstellar matter, and with recent experimental advancements in the experiments of H_2^+ using laser spectroscopy, it is of great important to study various properties of such a three-body system under the influence of screened Coulomb potentials: exp(−μr)/r, where μ is the screening parameters. In this work, we have estimated the critical range of screening parameters to establish Borromean windows for H_2^+ for each partial wave states up to $L = 4$.

Reference

[1] S. Kar and Y. K. Ho, *Chem. Phys. Lett.* **506**, 282 (2011), references therein.
Acknowledgments: YKH is supported by NSC of Taiwan. SK is supported by NSRIF in HIT.

Correlation and relativistic effects for the 4*f* – *nl* and 5*p* – *nl* multipole transitions in Er-like tungsten

U. I. Safronova* and A. S. Safronova

Physics Department, University of Nevada, Reno, NV 89557, USA
**ulyanas@unr.edu*

Relativistic and correlation effects are important in calculations of atomic data for low-ionized W ions. Wavelengths, transition rates, and line strengths are calculated for the multipole (E1, M1, E2, M2, and E3) transitions between the excited [Cd]$4f^{13}5p^6nl$, [Cd]$4f^{14}5p^5nl$ configurations and the ground [Cd]$4f^{14}5p^6$ state in Er-like W^{6+} ion ([Cd]=[Kr]$4d^{10}5s^2$). In particular, the relativistic many-body perturbation theory (RMBPT), including the Breit interaction, is used to evaluate energies and transition rates for multipole transitions in this hole-particle system. This method is based on RMBPT that agrees with MCDF calculations in lowest-order, includes all second-order correlation corrections and corrections from negative-energy states. The calculations start from a [Cd]$4d^{14}5p^6$ Dirac-Fock (DF) potential. First-order perturbation theory is used to obtain intermediate-coupling coefficients, and second-order RMBPT is used to determine the multipole matrix elements needed for calculations of other atomic properties [1]. In addition, core multipole polarizability is evaluated in random-phase and DF approximations. These are the first *ab initio* calculations of energies and transition rates in Er-like tungsten. This research was supported by DOE under OFES grant DE-FG02-08ER54951.

Reference

[1] U. I. Safronova, A. S. Safronova *Wavelengths and transition rates for nl — n'l' transitions in Be-, B-, Mg-, Al-, Ca-, Zn-, Ag- and Yb-like tungsten ions*, J. Phys. B **43**, pp. 074026 (2010).

EIT-based all-optical switching and cross-phase modulation under the influence of four-wave mixing

Meng-Jung Lee, Yi-Hsin Chen, I-Chung Wang, and Ite A. Yu*

Department of Physics and Frontier Research Center on Fundamental and Applied Sciences of Matters, National Tsing Hua University, Hsinchu 30013, Taiwan
**yu@phys.nthu.edu.tw*

Photons are superior information carriers and, consequently, manipulation of photon states, such as all-optical switching (AOS) and cross-phase modulation (XPM), has been considered as a promising means in quantum communication and quantum computation. Due to large nonlinear susceptibilities at low-light levels, the AOS and XPM based on the EIT effect make the single-photon operation feasible. However, existence of the four-wave mixing (FWM) process greatly reduces the switching or phase-modulation efficiency and hinders the single-photon operation. Here, we experimentally and theoretically demonstrated that an optimum switching detuning makes the switching efficiency in the EIT-based AOS reach the ideal efficiency even under the influence of FWM [1]. The results of this work can be directly applied to the EIT-based XPM. Our study provides useful knowledge for the research field of low-light-level or single-photon AOS and XPM in FWM-allowed systems.

Reference
[1] M. J. Lee, Y. H. Chen, I. C. Wang, and I. A. Yu, Opt. Express **20**, 11057 (2012).

Polarization of a focussed beam – Magneto Orbital Dichroism

Renaud Mathevet[1,2,*], Bruno Viaris de Lesegno[3], Laurence Pruvost[3], and Geert L. J. A. Rikken[1,2]

1. Laboratoire National des Champs Magnétiques Intenses, CNRS-INSA-UJF-UPS, 143 avenue de Rangueil, F31400 Toulouse, France
2. Université de Toulouse, LNCMI-T, F-31062 Toulouse, France
3. Laboratoire Aimé Cotton, CNRS II, Université Paris Sud, 91405 Orsay, France
**renaud.mathevet@lncmi.cnrs.fr*

We present two experiments involving the interplay between the shape and the polarization of a light beam.

It can be shown [1] that a gaussian focussed beam, asymptotically linearly polarized, acquires through propagation a small circular component, essentially in the Rayleigh range around the focal point. Following [2], we experimentally investigate this effect using Magneto-Circular-Dichroism, *i. e.* differential absorption of the right and left circular components induced by a magnetic field.

We also searched for an analog of MCD using the *orbital* angular momentum of the beam instead of the *intrinsic* angular momentum associated with circular polarization. The effect, if non-zero for the chosen transition around 808.5 nm in Nd:YAG, is at least three orders of magnitude smaller than MCD for $\ell = \pm 1$ Laguerre-Gauss beams.

References
[1] Davis, L. W., "Theory of Electromagnetic Beams", Phys. Rev. A, **19**, 1177 (1979).
[2] Yang, Nan and Cohen, Adam E., "Local Geometry of Electromagnetic Fields and Its Role in Molecular Multipole Transitions", J. Phys. Chem. B **115**, 5304 (2011).

Superparabolic level glancing models

J. Lehto* and K.-A. Suominen

Turku Centre for Quantum Physics, University of Turku, Finland
**jaakko.lehto@utu.fi*

Level crossing models for two-state quantum systems provide an important tool for the study of quantum dynamics in a wide variety of physical problems. The most prominent example of these models, the Landau-Zener model [1], has been successfully applied in many situations over the years. In the recent years, however, there has been a growing interest to study more general dynamics than given by the LZ case [2]. We address and discuss the basic characteristics of the special case of superparabolic level glancing, i.e., when the detuning is proportional to an even power of time and the energy levels reach a degeneracy at a specific point of time but do not actually cross.

References

[1] C. Zener, Proc. R. Soc. Lond. A **137**, 696 (1932).
[2] N. V. Vitanov and K.-A. Suominen, Phys. Rev. A **59**, 4580 (1999).

A Raman-Ramsey measurement of the third-order electric polarizability of the cesium ground state using a thermal atomic beam

Paul Knowles*, Jean-Luc Robyr, and Antoine Weis

Department of Physics, University of Fribourg, CH–1700, Switzerland
**paul.knowles@unifr.ch*

The experiment proposed in [1] for an independent measurement of the third order scalar polarizability of the ground state hyperfine structure in Cs, motivated by the 5σ discrepancy between the modern experimental values (Paris[2] with 0.2% precision, and Torino[3] with 2% precision) has produced a result [4], independently verifying the Paris [2] measurement. Details of our experiment, the results, and the limiting systematic effects will be presented.

References

[1] J.-L. Robyr, P. Knowles, and A. Weis, Proccedings of the IEEE International Frequency Control Symposium, 2009, Joint with the 22nd European Frequency and Time forum. pp. 600–603 (2009).
[2] P. Rosenbusch, S. Zhang, and A. Clairon. Proccedings of the IEEE International Frequency Control Symposium, 2007, Joint with the 21st European Frequency and Time forum. pp. 1060–1063 (2007).
[3] A. Godone, *et. al.* Phys. Rev. A, **71**(6) 063401, (2005).
[4] J.-L. Robyr, Doctoral Dissertation, University of Fribourg, Switzerland, (2011).

Larmor frequency dressing by a non-harmonic transverse magnetic field

G. Bevilacqua*, V. Biancalana, Y. Dancheva, and L. Moi

CNISM, CSC and Dipartimento di Fisica, Università di Siena, via Roma 56, 53100 Siena, Italy
**giuseppe.bevilacqua@unisi.it*

We present a theoretical and experimental study of spin precession in the presence of both a static and an orthogonal oscillating magnetic field, which is non-resonant, not harmonically related to the Larmor precession and of arbitrary strength. Due to the intrinsic non-linearity of the system, previous models that account only for the simple sinusoidal case cannot be applied. We suggest an alternative approach and develop a model that closely agrees with experimental data produced by an optical-pumping atomic magnetometer. We demonstrate that an appropriately designed non-harmonic field makes it possible to extract a linear response to a weak dc transverse field, despite the scalar nature of the magnetometer, which normally causes a much weaker, second-order response.

Effect of pulse shape on excitation line width for coherently driven two-level systems: power narrowing

Iavor I. Boradjiev* and Nikolay V. Vitanov

Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria
**boradjiev@phys.uni-sofia.bg*

We consider the phenomenon of decreasing of the spectral line width with increasing the coupling strength (power narrowing) for the case of two-level system coherently driven by a bell-shaped symmetrical pulse, and a constant detuning. Specifically, we consider couplings with exponentially and power-low falling wings. Picturing the problem in the adiabatic basis, by means of analysis of the adiabatic condition, we show that power narrowing is possible when the asymptotic behavior of the coupling function is given by a power-low [$\sim (t / T)^{-q}$]. The results are of potential application in high-precision spectroscopy.

Electromagnetically induced transparency using evanescent fields in warm atomic vapour

R. Thomas*, C. Kupchak, and A. I. Lvovsky

Institute for Quantum Information Science, University of Calgary, Calgary, Alberta T2N 1N4, Canada
**rjthomas@ucalgary.ca*

We investigate EIT in a dense rubidium vapour ($N^{1/3}\lambda > 1$) using selective reflection from a glass-vapour interface near the critical angle for total internal reflection. At incident angles above the critical angle, where the fields are evanescent, we observe a distinctly non-Lorentzian transmission window in the presence of a control field. The window exhibits a sharp cusp whose minimum width was measured to be 1 MHz, which is strong evidence for EIT as the natural line width of the transition is 6 MHz [1]. Furthermore, we investigate the effects of EIT on both the lateral and angular Goos-Hänchen shifts by measuring the position of a Gaussian beam using a balanced detector. A theoretical model describing both the spectrum of the reflected light field and the measured beam shifts is presented and compared to the experimental data. The possibility of light storage and applications to fundamentally compact frequency references [2] and frequency selective beam displacers are discussed.

References

[1] Petr Anisimov and Olga Kocharovskaya, J. Mod. Opt. **55**, 3159 (2008).
[2] J. Vanier, Appl. Phys. B **81**, 421 (2005).

Nonlinear magneto-optical effects with cold rubidium atoms

A. Wojciechowski*, K. Sycz, J. Zachorowski, and W. Gawlik

Center for Magneto-Optical Research, M. Smoluchowski Institute of Physics
Jagiellonian University, Kraków, Poland
**a.wojciechowski@uj.edu.pl*

We present results of our latest experiments on magneto-optical effects in laser-cooled non-degenerate rubidium samples. Interaction of atoms with a linearly polarized light leads to an effective creation of long-lived ground-state Zeeman coherences, which is observed through the nonlinear Faraday effect [1] or free induction decay signals of the Larmor precession. Coherence life-times of up to a few milliseconds are observed in a simple magnetic shield. Application of these effect to the precision magnetometry and its potential limits are presented. Moreover, Zeeman coherences form a versatile tool for studying superposition states which are vital to fundamental atomic physics and quantum information. We demonstrate the dynamics of coherent superposition states under the influence of laser and magnetic fields. Finally, we discuss a new scheme utilizing chirped pulses to virtually instantly create maximum allowed Zeeman coherences [2].

References

[1] A. Wojciechowski, E. Corsini, J. Zachorowski, and W. Gawlik, *Nonlinear Faraday rotation and detection of superposition states in cold atoms*, PRA **81**, 053420 (2010).
[2] G. P. Djotyan *et al.*, *Creation and measurement of cohrent superposition states in multilevel atoms*, Proc. of SPIE **7998**, 79881A (2011).

Quantum optical effects seen in mesoscopic Rydberg atoms

S. Yoshida[1,*], J. Burgdörfer[1], S. Ye[2], and F. B. Dunning

1. Vienna University of Technology, Vienna, Austria (EU)
2. Rice University, Houston, Texas, USA
**shuhei@concord.itp.tuwien.ac.at*

The direct UV photoexcitation of ground-state potassium atoms to high-lying ($n \sim 300$) Rydberg states in the presence of weak (< 5mV/cm) rf drive fields at, or near, the Kepler frequency of the final state (~ 230 MHz) is examined. The presence of the drive field leads to the appearance of new features in the excitation spectrum that depend sensitively on the strength and frequency of the field. These features are analyzed with the aid of Floquet theory. Even though very-high-n states are close to the classical limit, evidence of quantum optical effects such as electromagnetically induced transparency and the Autler-Townes splitting can be seen. For weak drive fields the spectra show linear and (small) quadratic energy shifts. With increasing drive field strengths the spectra become more complex as multiphoton transitions become important.

Research supported by the NSF, the Robert A. Welch Foundation, and by the FWF (Austria).

Laser driven ionization of alkali vapors in an ethane buffer gas by D1 and D2 laser light

Michael K. Shaffer*, Grady T. Phillips, Boris V. Zhdanov, Keith A. Wyman, and Randy J. Knize

US Air Force Academy, Colorado Springs, Colorado, USA
**Michael.Shaffer.ctr@usafa.edu*

Recently, there has been renewed interest in the dynamics of laser driven ionization of alkali metal vapors in a noble gas/ hydrocarbon buffer gas. Of particular concern is ionization driven by the resonant D1 and D2 light, the environment found in an operating alkali vapor laser[1]. Multistage photo excitation to high lying states is commonly observed and can lead to ionization via direct photo ionization or several collision mechanisms[2]. Our investigation considers two common alkali laser systems where either ^{133}Cs or ^{85}Rb vapors (~10^{13} atoms/cm^3) with 500 Torr of methane, ethane and/or helium buffer gas are the gain media. The alkali systems will be pumped with 0-20W of laser light driving the $n^2S_{1/2} \rightarrow n^2P_{3/2}$ transition at intensities of ~2kW/cm^2, will relax to the $n^2P_{1/2}$ state via buffer gas collisions, and will lase on the $n^2P_{1/2} \rightarrow n^2S_{1/2}$ transition with intensities of ~ 1kW/cm^2. A combination of optical and in situ electrical techniques is used to characterize the system.

References

[1] R. J. Knize, B. V. Zhdanov, and M. K. Shaffer, “Photoionization in alkali lasers”, Opt. Express **19** (8), pp. 7894 (2011).
[2] A. G. Leonov, D. I. Chekhov, A. N. Starostin, “Mechanisms of resonant laser ionization”, JEPT **84** (4), pp. 703 (1997).

QED theory of the multiphoton cascade transitions in hydrogen and its application to the cosmological hydrogen recombination

Timur Zalialiutdinov, Dmitry Solovyev, and Leonti Labzowsky*

Department of Physics, Saint-Petersburg State University, Saint-Petersburg, Russia
**leonti@landau.phys.spbu.ru*

Accurate theory of the multiphoton transitions in hydrogen with cascades is formulated on the basis of QED. As it was discovered in [1], [2] the 2-photon decay of 2*s* level led to the escape of radiation from the matter and allowed for the hydrogen recombination in the early universe. The escaped radiation is observed now as Cosmic Microwave Background (CMB) which properties were measured recently with high accuracy with the cosmic telescopes, providing the knowledge about the hydrogen recombination epoch. Recently it was suggested that the two-photon radiation from the excited $ns(n>2), nd$ levels could give a sizable contribution to the recombination process [3]. Unlike 2*s* case, the decay of the higher excited levels contains the cascade contribution. The description of such decays requires more careful treatment on the basis of QED. We present also a QED theory of the radiation escape for the model of the universe containing only two atoms. This model allows to estimate the role of the two- and three-photon escape from $ns(n>2), nd$ levels compared to the role of 2*s* level. The estimate predicts a correction of 0.2% which has to be taken into account at the recent level of the CMB measurements.

References

[1] Ya. B. Zel'dovich, V. G. Kurt and R. A. Sunyaev, Zh. Eksp. Teor. Fiz. **55**, 278 (1968).
[2] P. J. E. Peebles, Astrophys. J. **153**, 1 (1968).
[3] V. K. Dubrovich and S. I. Grachev, Astronomy Letters **31** 359 (2006).

Coupling matter waves to nano-mechanical oscillators

Nicola Lo Gullo[1], G. Massimo Palma[2], Mauro Paternostro[3], and Th. Busch[1,4,*]

1. Department of Physics, University College Cork, Cork, Republic of Ireland
2. NEST Istituto Nanoscienze-CNR and Dipartimento di Fisica,
Univerisita' degli Studi di Palermo, Via Archirafi 36, I-90123 Palermo, Italy
3. Centre for Theoretical Atomic, Molecular and Optical Physics,
School of Mathematics and Physics, Queen's University, Belfast BT7 1NN, UK
4. Quantum Systems Unit, Okinawa Institute of Science and Technology, Okinawa, Japan
**Thomas.Busch@oist.jp*

We propose a scheme to probe the quantum coherence in the state of a nano-cantilever based on its magnetic coupling (mediated by a magnetic tip) with a spinor Bose Einstein condensate (BEC). By mapping the BEC into a rotor, its coupling with the cantilever results in a gyroscopic motion whose properties depend on the state of the cantilever: the dynamics of one of the components of the rotor angular momentum turns out to be strictly related to the presence of quantum coherence in the state of the cantilever. [1]

Reference

[1] N. Lo Gullo, Th. Busch, G. M. Palma, and M. Paternostro, *Probing mechanical quantum coherence with an ultracold-atom meter*, Phys. Rev. A **84**, 063815 (2011).

Searching for cosmological spatial variations in values of fundamental constants using laboratory measurements

Julian Berengut and Victor Flambaum

School of Physics, University of New South Wales, Sydney NSW 2052, Australia

The results of a very large study of around 300 quasar absorption systems provide hints that there is a spatial gradient in the variation of the fine structure constant, α [1]. In one direction on the sky α appears to have been smaller in the past, while in the other direction it appears to have been larger. A remarkable result such as this must be independently confirmed by complementary searches. We discuss how terrestrial measurements of time-variation of the fundamental constants in the laboratory, meteorite data, and analysis of the Oklo nuclear reactor can be used to corroborate the spatial variation observed by astronomers [2]. In particular we can expect the yearly variation of α in laboratory measurements to be $\dot{\alpha} / \alpha \sim 10^{-19}\ \mathrm{yr}^{-1}$. The required accuracy is two orders of magnitude below current atomic clock limits, but there are severalproposals that could enable experiments to reach it. These include nuclear clocks and transitions in highly-charged ions that would have very high sensitivity to α-variation.

References
[1] J. K. Webb, J. A. King, M. T. Murphy, V. V. Flambaum, R. F. Carswell and M. B. Bainbridge, Phys. Rev. Lett. **107**, 191101 (2011).
[2] J. C. Berengut and V. V. Flambaum, Europhys. Lett. **97**, 20006 (2012).

Beyond atomic physics Mo-210

A cavity nanoscope

Matthias Mader[1,2,*], Hanno Kaupp[1,2], Christian Deutsch[1,2,3], Jakob Reichel[3], Theodor W. Hänsch[1,2], and David Hunger[1,2]

1. Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 München, Germany
2. Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
3. Laboratoire Kastler-Brossel, ENS, CNRS, UPMC, 24 rue Lhomond, 75005 Paris, France
**matthias.mader@physik.uni-muenchen.de*

We present a novel tool for extremely sensitive and spatially resolved absorption spectroscopy on nanoscale objects. To boost sensitivity, multiple interactions of probe light with an object are realized by placing the sample inside an optical scanning microcavity. It is based on a laser machined and mirror-coated end facet of a single mode fiber and a macroscopic plane mirror forming a fully tunable open access Fabry-Perot cavity [1]. Scanning the sample through the microscopic cavity modeyields a spatially resolved map of absorptivity of the sample.

We show first proof-of-principle experiments with single gold nanospheres and nanorods. We demonstrate polarization sensitive absorption measurements as well as measurements on dispersive and birefringent effects of the samples.

Reference
[1] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch and J. Reichel *A fiber Fabry-Perot cavity with high finesse* , New J. Phys. **12**, pp. 065038 (2010).

Control of high harmonic generation by wave front shaping

A. A. Kolomenskii[1,*], M. Sayraç[1], E. Cook[1], J. Wood[1], R. Nava[1], J. Strohaber[1], G. G. Paulus[1,2], and H. A. Schuessler[1]

1. Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA
2. Institut für Optik und Quantenelektronik Max-Wien-Platz 1, 07743 Jena, Germany
**a-kolomenski@physics.tamu.edu*

The high harmonic generation (HHG) process enables an extension to the short wavelength EUV spectral region and is closely related to generation of attosecond laser pulses. In this process, electrons are first separated from their parent atoms by an intense incident electromagnetic wave, then accelerated in the laser field and can return with a change of the field direction, recombining with the parent atom and emitting energetic photons [1]. We produce HHG in Ar gas with 50fs laser pulses. To control HHG we use a spatial light modulator, shaping the wave front of the fundamental radiation by introducing spatially distributed phase delays. We show that by imposing appropriate phase structures on the fundamental beam the output of high harmonics can be enhanced many fold, and also interference phenomena in HHG can be observed. The extension of the EUV spectrum to shorter wavelength due to enhanced energy release in the electron-ion recombination is also possible. This work was supported by the Welch Foundation (grant No. A1546) and the NSF (grant No. 0722800).

Reference

[1] P. Corcum and F. Krausz, "Attosecond science", Nature. Physics **3**, pp. 3812-387 (2007).

White-light generation using spatially-structured beams of femtosecond radiation

N. Kaya[1,*], J. Strohaber[1], H. Schroeder[2], A. A. Kolomenskii[1], G. Kaya[1], G. G. Paulus[1,3], and H. A. Schuessler[1]

1. Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA
2. Max-Planck-Institut für Quantumoptik, 85748 Garching, Germany
3. Institut für Optik und Quantenelektronik Max-Wien-Platz 1, 07743 Jena, Germany
**necatiphy@gmail.com*

We studied white-light generation in water using spatially-structured beams of femtosecond radiation. By changing the transverse spatial phase of an initially Gaussian beam with a 1D spatial light modulator to that of Hermite–Gaussian modes ($HG_{n,m}$), we were able to generate beams exhibiting phase discontinuities and steeper intensity gradients. Under certain experimental conditions, when the spatial phase of an initial Gaussian beam (showing no significant white-light generation) was changed to that of a HG_{01}, or HG_{11} mode, a significant amount of white-light was generated. Because self-focusing is known to play an important role in white-light generation, the self-focusing lengths of the resulting transverse intensity profiles were used to explain this generation. Distributions of the laser intensity for beams having step-wise spatial phase variations were modeled using the Huygens-Fresnel-Kirchhoff integral in the Fresnel approximation and were found to be in excellent agreement with experiment. This work was supported by the Robert A. Welch Foundation (grant No. A1546), the National Science Foundation (grant No. 0722800).

Coherent control multi-dimensional Fourier transform spectroscopy

Jongseok Lim[1], Hangyeol Lee[1], Sangkyung Lee[2], and Jaewook Ahn[1,*]

1. Department of Physics, KAIST, Daejeon 305-701, Korea
2. Korea Research Institute of Science and Standards, Daejeon 305-340, Korea
**jwahn@kaist.ac.kr*

We present a method that harnesses coherent control capability to two-dimensional Fourier-transform optical spectroscopy. For this, three ultrashort laser pulses are individually shaped to prepare and control the quantum interference involved in two-photon interexcited-state transitions of a V-type quantum system. In a three-pulse coherent control experiment of atomic rubidium, the phase and amplitude of controlled transition probability is retrieved from a two-dimensional Fourier-transform spectral peak and we show theoretically and experimentally that two-photon coherent control in a V-shape three-level system projects a one-photon coherent transient in a simple two-level system. The second- and third-order spectral phase terms of a shaped laser pulse play the roles of time and quadratic spectral phase, respectively, in conventional coherent transients [1, 2].

References

[1] J. Lim, H. Lee, J. Kim, S. Lee, and J. Ahn, *Coherent transients mimicked by two-photon coherent control of a three-level system*, Phys. Rev. A **83**, 053429 (2011).

[2] J. Kim, H. Lee, S. Lee, and J. Ahn, *Quantum control in two-dimensional Fourier-transform spectroscopy*, Phys. Rev. A **84**, 013425 (2011).

Precision attosecond physics with atomic hydrogen

W. C. Wallace[1,2], M. G. Pullen[1,2,*], D. E. Laban[1,2], A. J. Palmer[1,2], G. F. Hanne[3], A. N. Grum-Grzhimailo[4,5], K. Bartschat[4], I. Ivanov[6], A. Kheifets[6], H. M. Quiney[1,7], I. V. Litvinyuk[2], R. T. Sang[1,2], and D. Kielpinski[1,2,*]

1. ARC Centre of Excellence for Coherent X-Ray Science and
2. Australian Attosecond Science Facility and Centre for Quantum Dynamics, Griffith University, Brisbane, Australia
3. Atomic and Electronics Physics Group, Westfälische Wilhelms-Universität, Münster, Germany
4. Department of Physics and Astronomy, Drake University, Des Moines, Iowa, USA
5. Institute of Nuclear Physics, Moscow State University, Moscow, Russia
6. Research School of Physical Sciences, The Australian National University, Canberra, Australia
7. Department of Physics, University of Melbourne, Melbourne, Australia
**d.kielpinski@griffith.edu.au*

We have performed the first investigations of the ionisation dynamics of atomic hydrogen (H) by strong-field few-cycle laser pulses. We demonstrate quantitative agreement between *ab initio* theory and experiment at the 10% level over an unprecedented range of laser intensity and electron energy [1] and use the results to perform laser intensity calibration with 1% accuracy. We present initial measurements of carrier-envelope phase (CEP) dependence of the H photoelectron yield, which will enable accurate *ab initio* calibration of absolute laser CEP.

Reference

[1] M. G. Pullen *et al.*, *Experimental ionization of atomic hydrogen with few-cycle pulses*, Opt Lett **36**, pp. 3660-3662 (2011).

Monte Carlo simulations of an unconventional phase transition for a 2d dimerized quantum Heisenberg model

F.-J. Jiang

Department of Physics, National Taiwan Normal University, 88, Sec.4, Ting-Chou Rd., Taipei 116, Taiwan
fjjiang@ntnu.edu.tw

Motivated by the indication of a new critical theory for the spin-1/2 Heisenberg model with a spatially staggered anisotropy on the square lattice, we re-investigate the phase transition of this model induced by dimerization using first principle Monte Carlo simulations. We focus on studying the finite-size scaling of $\rho_{s1}2L$ and $\rho_{s2}2L$, where L stands for the spatial box size used in the simulations and ρ_{si} with $i \in \{1, 2\}$ is the spin-stiffness in the i-direction. Remarkably, while we observe a large correction to scaling for the observable $\rho_{s1}2L$, the data for $\rho_{s2}2L$ exhibit a good scaling behavior without any indication of a large correction. As a consequence, we are able to obtain a numerical value for the critical exponent ν which is consistent with the known $O(3)$ result with moderate computational effort. Specifically, by fitting the data points of $\rho_{s2}2L$ to their expected scaling form, we obtain $\nu = 0.7120(16)$ which agrees quantitatively with the most accurate known Monte Carlo $O(3)$ result $\nu = 0.7112(5)$.

Reference

[1] F.-J. Jiang, Phys. Rev. B **85**, 014414 (2012).

Active control of magnetic field and gradient in ultracold experiments

Chang Chi Kwong[1,*], Pramod Mysore Srinivas[2], Zhong Yi Chia[2], Yang Tao[2], Elnur Hajiyev[2], Frédéric Leroux[2], and David Wilkowski[1,2,3]

1. School of Physical and Mathematical Science, Nanyang Technological University, Singapore
2. Center for Quantum Technologies, National University of Singapore, Singapore
3. Institut Non Linéaire de Nice, CNRS/Université de Nice Sophia Antipolis, Valbonne, France
**kwon0009@e.ntu.edu.sg*

Work has been carried out to design a magnetic field and gradient compensation system for ultracold strontium experiment. A total of eight magnetic sensors (with 3-axis measurements) are arranged in a cuboid configuration around the atomic cloud. An active compensation system is being designed, with the measurement outcomes feedback electronically to adjust the current flowing through the compensation coils. Both the unwanted A.C. and D.C. components of the magnetic field and gradients, $\frac{\partial B_x}{\partial x}$, $\frac{\partial B_y}{\partial y}$ and $\frac{\partial B_z}{\partial z}$, can then be compensated. Additional information on the curvature of the magnetic field can be deduced from the measurements to give a more detailed information of the magnetic field around the atomic cloud. This system should enable the control of magnetic field below the level of 0.1 mG for for the ultracold strontium experiment.

Random laser in cold atoms

Quentin Baudouin[1], Nicolas Mercadier[1,2], Vera Guarrera[1,3], and Robin Kaiser[1,*]

1. Institut Non-Linéaire de Nice, CNRS, Université de Nice Sophia Antipolis, Valbonne, France
2. now with Saint-Gobain (Paris)
3. now in TU Kaiserslautern
**robin.kaiser@inln.cnrs.fr*

Random lasing in a medium with scattering and gain has been predicted by V. Letokhov [1] with threshold is given by a critical size of the medium required to overcome losses via scatetring through the surface. Such random lasing has is also under investigation in astrophysical systems [2], where non thermal equilibrium coniditions can exist in dilute cloud of plasma. Many random lasers based on condensed matter systems have been realized in the last 25 years, but the existence of gaz lasers, the realization of random lasing in dilute atomic vapours has not been reported. We show that a cloud of cold atoms can be a good tool to study random laser with resonance scattering feedback [3]. Using two photon hyperfine Raman gain with the incident laser tuned to an atomic line provinding enhanced scattering for the anti-stockes photon, gain and scattering have been combined with a single atomic species of ^{85}Rb. We observe signatures of random lasing in the total emission which displays a threshold behaviour with optical thickness of the cloud.

References
[1] V. S. Letokhov, Sov. Phys. JETP 26,835 (1968).
[2] V. S. Letokhov and S. Johansson,Astrophysical Lasers, Oxford (2009).
[3] L. Froufe-Pérez, W. Guerin, R. Carminati and R. Kaiser, Phys. Rev. Lett,102,173903 (2009).

Information-theoretic properties of Rydberg atoms

Irene Valero[1,2], Sheila Lopez-Rosa[1,3], P. Sánchez-Moreno[1,4], and Jesus S. Dehesa[1,2,*]

1. Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Spain
2. Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, Spain 3. Departamento de Física Aplicada, Universidad de Sevilla, Spain
4. Departamento de Matemática Aplicada, Universidad de Granada, Spain
**dehesa@ugr.es*

The internal disorder of Rydberg atoms as contained in their position and momentum probability densities is examined by means of the following spreading and information-theoretic quantities: the radial and logarithmic expectation values, the Shannon entropy and the Fisher information. The leading term of these quantities is rigorously calculated by use of the asymptotic properties of the concomitant entropic functionals of the Laguerre and Gegenbauer orthogonal polynomials which control the wavefunctions of the Rydberg states in both position and momentum spaces. The associated generalized Heisenberg-like, logarithmic and entropic uncertainty relations are also given. Finally, application to the experimentally accesible linear ($l = 0$), circular ($l = n - 1$) and quasicircular ($l = n - 2$) states is explicitly done.

Reference
[1] S. Lopez-Rosa, I. Valero, P. Sánchez-Moreno and J. S. Dehesa, "Information-theoretic properties of Rydberg atoms", Preprint UGR 2012, submitted.

Fault of interferometer passbands equidistance with its length variation

Alexander K. Dmitriev[1,2,*], Nickolai N. Golovin[1], and Alexei A. Lugovoy[2]

1. Novosibirsk state technical university , Novosibirsk, Russia
2. Institute of laser physics of SB RAS , Novosibirsk, Russia
**alexander_dmitriev@ngs.ru*

It is well known, when a plane electromagnetic wave passing through an interferometer (for example Fabry-Perot or Michelson) its transmission bands are equidistant with an interval equal to radiation half wavelength. This has been the basis for creating the optical ruler, in which stabilized laser wavelength serves as the reference length [1]. The femtosecond laser [2] can be used for creation of the length standard too. In the present study it was found that the shape of the interferometer passbands is asymmetric due to laser beam divergence. Physics of this phenomenon is caused by the difference between wavefront curvatures of interfering light beams. It is shown that the asymmetry of the bands depends on the different factors: interferometer length, mirror displacement relative to the beam waist, the beam orificing at the photodetector, misalignment of the interferometer mirrors, mirror transmission.

References

[1] Quinn T. J. *Metrologia* **40,** 103 (2003).
[2] D. V. Basnak, A. K. Dmitriev, A. A. Lugovoy, P. V. Pokasov, Quantum Electronics, **38**, 187 (2008).

Enabling technologies for integrated atom chips

Matt Himsworth[1,*], Joseph Rushton[1], Tim Freegarde[1], and Michael Kraft[1,2]

1. School of Physics & Astronomy, University of Southampton, UK
2. School of Electronics and Computer Science, University of Southampton, UK
**m.d.himsworth@soton.ac.uk*

Atomic physics experiments based on ultracold atoms have a wide range of applications beyond the laboratory as time and metrological standards, inertial guidance sensors, gravitational field sensors, magnetometers, and they are likely to play a crucial part in emerging quantum based technologies such as cryptography, quantum simulators, networks and information processing. Over a decade of research has been devoted to translating these experiments onto microfabricated platforms known as atom chips. These are, however, far from ‘lab-on-a-chip’ and remain firmly ‘chip-in-a-lab’ devices. This is due to the need for a vast infrastructure of UHV systems, atom sources, laser systems and detectors, which have yet to be completely miniaturized. Our research is directed at tackling this problem by identifying and adapting materials and methods from the planar micro/nanofabrication industry to perform the roles of standard atomic physics apparatus in an integrated and mass-manufacturable way. Our initial studies into obtaining, maintaining and measuring ultrahigh vacuum in a micro-litre cavity are presented as well as integrated atom sources and novel magneto-optical trap geometries.

Tuesday Posters

Matter-wave interferometry with charged particles

Alexander Stibor[1,*], Alexander Rembold[1], Georg Schütz[1], Andreas Pooch[1], Franz Hasselbach[2], and Ing-Shouh Hwang[3]

1. Quantum-Ion-Interferometry, Institute of Physics, University of Tübingen, Tübingen, Germany
2. Institute of Applied Physics, University of Tübingen, Tübingen, Germany
3. Institute of Physics, Academia Sinica, Taipei, Taiwan R.O.C.
**alexander.stibor@uni-tuebingen.de*

Important achievements have been accomplished until now in neutral particle interferometry. To extend this field of research to charged matter-waves, we present the design and current status in the construction of the first stable interferometer for ions and charged molecules. It potentially combines the advantages of electron, atom and molecule interferometry: the high technical standard in the generation, detection and precise control of electron beams can be applied on ions together with the possibility of laser manipulation of ionic states or thermal rovibrational excitation in charged molecules. Such an interferometer can cover fundamental Aharonov-Bohm experiments that were up to now mainly accessible for pointlike electrons, for particles with inner structure and test gauge and decoherence theories. In our setup, a stable and coherent ion beam will be separated and recombined by a fine charged biprism wire. The longitudinal coherence is adjusted by a Wien-filter and the interference pattern is detected after a quadrupole magnification. We also discuss future applications for ion-interferometers as highly sensitive, compact sensors for rotation and acceleration.

Atom interferometry Tu-002

Limit to spin squeezing in finite temperature Bose-Einstein condensates

Alice Sinatra[1,*], Yvan Castin[1], and Emilia Witkowska[2]

1. Laboratoire Kastler Brossel, CNRS/UPMC, Paris, France
2. Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
**alice.sinatra@lkb.ens.fr*

Quantum correlations could be used in atomic clocks and interferometers to increase their sensitivity with respect of using uncorrelated atoms. A simple class of states useful for metrology are *spin squeezed states*. Recently such states could be obtained using interactions in condensates with two internal states [1]. A crucial question is the scaling of the spin squeezing (or metrology gain) with the atom number. We show that, at finite temperature, the maximum spin squeezing achievable using interactions in Bose-Einstein condensates has a finite limit when the atom number $N \to \infty$ at fixed density and interaction strength. We calculate the limit of the squeezing parameter for a spatially homogeneous system and show that it is bounded from above by the initial non-condensed fraction [2].

References

[1] C. Gross, T. Zibold, E. Nicklas, J. Estève, M. K. Oberthaler, *Nonlinear atom interferometer surpasses classical precision limit*, Nature **464**, 1165 (2010);
M. F. Riedel, P. Böhi, Li Yun, T. W. Hänsch, A. Sinatra, P. Treutlein, *Atom-chip-based generation of entanglement for quantum metrology*, Nature **464**, 1170 (2010).

[2] A. Sinatra, E. Witkowska, J.-C. Dornstetter, Li Yun, Y. Castin, *Limit of Spin Squeezing in Finite Temperature Bose-Einstein Condensates*, Phys. Rev. Lett. **107**, 060404 (2011);
A. Sinatra, E. Witkowska, Y. Castin, *Spin Squeezing in Finite Temperature Bose-Einstein Condensates : Scaling with the system size*, arXiv:1112.3795.

Quantum metrology with a scanning probe atom interferometer

Caspar F. Ockeloen, Max F. Riedel, Roman Schmied, and Philipp Treutlein*

Department of Physics, University of Basel, Switzerland
**philipp.treutlein@unibas.ch*

Interferometers using N uncorrelated (non-entangled) particles are fundamentally limited by shot-noise to an interferometric phase uncertainty of $\Delta\varphi \geq 1/\sqrt{N}$. This *standard quantum limit* (SQL) is particularly relevant in applications such as electromagnetic field imaging, where the desired high spatial resolution forces one to work with small probe size (small N). Using entangled states, $\Delta\varphi$ could be reduced significantly, towards the Heisenberg limit $\Delta\varphi \geq 1/N$.

Here we report an atom-interferometric measurement of microwave fields from an integrated circuit, with an uncertainty of 4.0 dB below the SQL [1]. Our interferometer employs $N = 1300$ entangled atoms in a spin-squeezed state and maintains performance below the SQL for Ramsey interrogation times up to 20 ms. Using an atom chip, we spatially scan the spin-squeezed atoms over 10 μm while maintaining sub-SQL operation. We perform a quantum-state tomography of our interferometer input state [2], demonstrating a spin noise reduction of up to 4.5 dB and a spin coherence of > 98%, which implies a depth of entanglement of at least 40 particles. Our technique is promising for high-resolution imaging of electromagnetic fields near solid-state microstructures [3].

References

[1] C. F. Ockeloen, M. F. Riedel, R. Schmied, and P. Treutlein, to be published (2012).
[2] R. Schmied and P. Treutlein, New J. Phys. **13**, 065019 (2011).
[3] P. Böhi, M. F. Riedel, T. W. Hänsch, and P. Treutlein, Appl. Phys. Lett. **97**, 051101 (2010).

A trapped atom interferometer for short range forces measurements

Franck Pereira dos Santos*, Bruno Pelle, Adèle Hilico, Quentin Beaufils, Gunnar Tackmann, Sophie Pélisson, Riccardo Messina, Marie-Christine Angonin, and Peter Wolf

LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, LNE, Paris, France
**franck.pereira@obspm.fr*

We have demonstrated laser controlled tunneling of ^{87}Rb atoms in a vertical optical lattice using two- photon Raman transitions [1], allowing performing high resolution laser spectroscopy of Wannier Stark (WS) states. A sequence of such laser pulses is used to first split the atoms into neighboring WS states and later recombine them. This realizes a trapped atom interferometer, which, in our geometry, is sensitive to the difference in gravitational potential energies between the coupled WS states, allowing for a precise measurement of the Bloch frequency $\nu_B = mg\lambda/2h$, where m is the mass of the ^{87}Rb atom, g the gravity acceleration, and λ the lattice laser wavelength. We have reached a relative sensitivity on ν_B of 10^{-5} at 1 s. Performing this interferometer close to a reflecting surface, this sensitivity will allow performing measurements of Casimir Polder forces to better than 1% at distances of a few microns, and improving significantly tests of gravity at short range [2].

References

[1] Q. Beaufils, G. Tackmann, X. Wang, B. Pelle, S. Pélisson, P. Wolf and F. Pereira dos Santos, "Laser controlled tunneling in a vertical optical lattice", Phys. Rev. Lett. **106**, 213002 (2011).
[2] R. Messina, S. Pelisson, M.-C. Angonin, and P. Wolf, "Atomic states in optical traps near a planar surface", Phys. Rev. A **83**, 052111 (2011).

Long-lived coherence of an interacting Bose-Einstein condensate

Mikhail Egorov[1,2], Russell Anderson[1,2], Valentin Ivannikov[1], Bogdan Opanchuk[1], Peter Drummond[1], Brenton Hall[1], and Andrei Sidorov[1,*]

1. Swinburne University of Technology, Melbourne, Australia
2. Monash University, Melbourne, Australia
**asidorov@swin.edu.au*

We report that atomic interactions not only lead to quantum and spatial dephasing of a trapped BEC interferometer but also produce mean-field-driven rephasing through periodic collective oscillations. We observe the coherence of an interacting two-component Bose-Einstein condensate of ^{87}Rb atoms surviving for seconds in a Ramsey interferometer. Mean-field-driven collective oscillations of two components lead to periodic dephasing and rephasing of condensate wave functions with a slow decay of the interference fringe visibility. We apply spin echo synchronous with the self-rephasing of the condensate to reduce the influence of state-dependent atom losses, significantly enhancing the visibility up to 0.75 at the evolution time of 1.5 s. Mean-field theory consistently predicts higher visibility than experimentally observed values. We quantify the effects of classical and quantum noise and infer a coherence time of 2.8 s for a trapped condensate of 5.5×10^4 interacting rubidium atoms.

Reference

[1] M. Egorov, R. P. Anderson, V. Ivannikov, B. Opanchuk, P. Drummond, B. V. Hall, and A. I. Sidorov, "Long-lived periodical revivals of coherence in an interacting Bose-Einstein condensate", Phys. Review A **84**, p. 021605(R)-4 (2011).

Entanglement and optimized interferometric phase measurement

Q. Y. He, T. G. Vaughan, M. D. Reid, and P. D. Drummond*

Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne 3122, Victoria, Australia
**mdreid@swin.edu.au*

We derive a phase-entanglement criterion for two bosonic modes which is immune to number fluctuations. This also provides an operational definition of relative phase-measurements, via analysis of phase measurement in interferometry. We show that the new entanglement measure is directly proportional to enhanced phase-measurement sensitivity. As an example, we calculate the phase-entanglement of the ground state of a two-well, coupled Bose-Einstein condensate, similar to recent experiments[1]. We show that a new type of quantum squeezing is found, namely planar quantum squeezing [2], which squeezes two orthogonal spin directions simultaneously. This is possible owing to the fact that the SU(2) group that describes spin symmetry lives in a three-dimensional space, of higher dimension than the group for photonic quadratures. The advantage of planar spin-squeezing is that, unlike conventional spin-squeezing, it allows noise reduction over all phase-angles simultaneously.

References

[1] J. Esteve, C. Gross, A. Weller, S. Giovanazzi & M. K. Oberthaler, *Squeezing and entanglement in a Bose-Einstein condensate* Nature **455**, pp. 1216-1219 (2008).
[2] Q. Y. He, Shi-Guo Peng, P. D. Drummond, and M. D. Reid, *Planar quantum squeezing and atom interferometry*, Phys. Rev. A **84**, pp. 022107 (2011).

Gravitational output-coupling of an atom laser

Vasiliki Bolpasi[1,2], Michael Morrissey[1], and Wolf von Klitzing[1,*]

1. IESL-FORTH, Vassilika Vouton P.O. Box 1527, GR-71110 Heraklion Greece
2. Physics Department, University of Crete, GR711 03, Heraklion Crete, Greece
**wvk@iesl.forth.gr*

In this poster we present a novel type of output coupling of an atom-laser from a BEC. Traditional output couplers either use a weak RF field [1] or a weak Bragg beam [2] to resonantly outcouple a small fraction of the BEC. The gravitational output coupler, presented here, uses a *strong* RF field to *dress* the trapping potential of a Ioffe-Pritchard magnetic trap such, that a small hole is created in the very bottom of the trap. The gravitational output coupler is fully coherent: Whereas the outcoupled atoms of weak RF are distributed over a range of magnetic hyperfine states, the ones of the gravitational output coupler are all in the $m_F = 2$ state. This not only increases thebrightness of the atom laser by a factor of 5, but also raises the spectre of a reversible atom laser, where the beam not only exits, but also enters a BEC. We demonstrate well-collimated atom beams – both of thermal and condensed origin – and discuss their transverse coherence.

References
[1] I. Bloch, T. W. Hänsch, and T. Esslinger, *Atom Laser With a CW Output Coupler*, Phys. Rev. Lett. **82-15**, pp. 3008–3011 (1999).
[2] E. W. Hagley *et al. A Well-Collimated Quasi-Continuous Atom Laser* Science **283:5408**1706-1709 (1999).

Interferometry with chip-based atom lasers in microgravity

Naceur Gaaloul*, Wolfgang Ertmer and Ernst Rasel, for the QUANTUS cooperation

QUEST, Institute of Quantum Optics - Leibniz University, Hanover, Germany
**gaaloul@iqo.uni-hannover.de*

We report on the implementation of a Bragg-type interferometer operated with a chip-based atom laser for Rubidium ^{87}Rb. With the chip based atom laser we can generate thermal ensembles as well as Bose-Einstein condensates (BEC)[1]. With the help of delta-kick cooling [2], implemented via the atom chip, we can further slow down the expansion of thermal and condensed atoms. In addition, the chip allows transferring atoms in the individual Zeeman states of the two hyperfine ground states, in particular into the non-magnetic state. With this toolbox we could extend the observation of a BEC of only 10^4 atoms up to two seconds. Benefiting from the extended free fall in microgravity we could combine this with an asymmetric Mach-Zehnder type interferometer over hundreds of milliseconds to study the coherence and to analyze the delta kick cooling with the help of the observed interference fringes.

References
[1] T. van Zoest *et al.*, "Bose-Einstein condensation in microgravity", Science **328**, pp 1540 (2010).
[2] H. Amman and N. Christensen, "Delta Kick Cooling: A New Method for Cooling Atoms", Phys. Rev. Lett., 78, pp 2088 (1997).

Measuring small energy differences by BEC interferometry on a chip

B. Yuen, I. J. M. Barr, J. P. Cotter, F. Baumgärtner, R. J. Sewell, S. Eriksson
I. Llorente-Garcia, J. Dingjan, and E. A. Hinds

Centre for Cold Matter, Imperial College London, Prince Consort Road, London SW7 2BW, UK

We investigate the use of a Bose-Einstein condensate trapped on an atom chip for making interferometric measurements of small energy differences[1,2]. A nearly pure condensate is split horizontally using an RF magnetic field. A relative height difference between the clouds is introduced through adjustment of the RF field. The trap is turned off allowing the clouds to interfere in free fall. For varying height separations we measure the relative phase difference between the clouds from the observed fringes in the atomic density distribution. We measure and explain the noise in the energy difference of the condensates, which derives from the binomial distribution in the number difference. An energy difference of 2.17(32) Hz/nm ismeasured, as expected from Earth's gravity. We have considered systematic errors and are now working towards more precise control of the atoms. This will improve the accuracy that the interferometer can achieve.

References

[1] R. J. Sewell *et. al.*, *Atom chip for BEC interferometry*, J. Phys. B. **43** 051003 (2010).
[2] F. Baumgärtner *et. al.*, *Measuring energy differences by BEC interferometry on a chip*, Phys. Rev. Letts. **86**, 1195-1198 (2010).

A compact and transportable cold atom inertial sensor for space applications

Pierre-Alain Gominet[1,*], Vincent Ménoret[1], Baptiste Battelier[1], Nassim Zahzam[2], Alexandre Bresson[2],Arnaud Landragin[3], and Philippe Bouyer[1]

1. LP2N, Université Bordeaux I, IOGS, CNRS, 351 cours de la Libération, 33405, Talence, France
2. ONERA The French Aerospace Lab, F-91761 Palaiseau, France
3. LNE-SYRTE, Observatoire de Paris, CNRS et UPMC, Paris, France
**pierre-alain.gominet@institutoptique.fr*

We have developped a compact, robust and transportable cold atom inertial sensor to test the Univarsility of Free-Fall (UFF) during parabolic flights. Our system uses laser pulses to measure the acceleration of a cloud of cold ^{87}Rb atoms. The laser source is based on telecom technology and can be operated in difficult environments [1]. We reject vibrations by correlating the atom sensor with an external mechanical accelerometer [2].

The next step, by adding another atomic species (^{39}K) to our system, is to perform a test of UFF. We have constructed a dual-wavelength laser system and performed simultaneous cooling of Rb and K in two species MOT. We will then use the atom interferometer to measure the differential acceleration between the two atom clouds in free-fall. This will be an important step towards a space-based test at the level 10^{-15}, such as the one planed in the frame of ESA's STE-QUEST mission [3].

References

[1] V. Ménoret *et al.*, Optics Lett. **36**, 21 (2011).
[2] R. Geiger *et al.*, Nature Communications **2**, 474 (2011).
[3] http://sci.esa.int/ste-quest-doi2011.

Matter-wave interferometry with single bright solitons

Paul Dyke*, Sidong Lei, and Randall G. Hulet

Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA
**paul.dyke@rice.edu*

Bright solitons [1, 2] are suitable candidates for matter-wave interferometry due to their self focusing, and non-dispersive nature. In our experiments, we use the broad Feshbach resonance of ^{7}Li in the $|1,1\rangle$ state to tune the scattering length through zero to small negative values to form a single bright matter wave soliton close to the critical number for collapse. The soliton is confined to a 1D potential formed from a single focused laser beam, which is weakly confining in the axial direction. We excite the collective dipole mode of the soliton and investigate the interaction with a thin potential barrier formed by a near-resonant, blue detuned, cylindrically focused laser beam that perpendicularly bisects the trapping beam at its focus. Through adjustment of the barrier potential, the soliton can either be split in two, transmitted or reflected. By applying a phase imprinting beam to one arm of the split soliton we study the phase dependent interactions on the subsequent barrier interaction.

References

[1] L. Khaykovich *et al.*, *Formation of a bright matter wave soliton*, Science **296**, pp. 1290-1293 (2002).
[2] K. E. Strecker *et al.*, *Formation and propagation of matter-wave soliton trains*, Nature **417**, pp. 150-153 (2002).

Highly-charged ions as a basis of optical atomic clockwork of superb accuracy

Andrei Derevianko[1,*], V. A. Dzuba[1,2], and V. V. Flambaum[2]

1. Department of Physics, University of Nevada, Reno, Nevada 89557, USA
2. School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
**andrei@unr.edu*

State of the art clocks carry out frequency measurements at the eighteenth decimal place [1]. As the projected “end-of-the-road” fractional accuracy of such clocks is at the level of 10^{-18}, it is natural to wonder how to extend the accuracy frontier even further. While the nuclear clock [2] holds a promise of a projected accuracy at the improved 10^{-19} level, it relies on a yet unobserved optical transition in the radioactive ^{229}Th nucleus. Considering large uncertainties of nuclear models, the frequency of that transition can not be reliably computed. Here we show that the nuclear clock performances can be replicated with atomic systems, fully overcoming these challenges. We identify several highly-forbidden laser-accessibe transitions in heavy stable isotopes of highly-charged ions (HCI) that may serve as clock transitions. Similarly to the singly-charged ions of modern clocks [1], HCIs can be trapped and cooled. The key advantage of HCIs comes from their higher ionic charge. As the ionic charge increases, the electronic cloud shrinks thereby greatly reducing couplings to detrimental external perturbations. Our analysis of various systematic effects for several HCIs demonstrates the feasibility of attaining the 10^{-19} accuracy mark.

References

[1] C. W. Chou *et al.*, Phys. Rev. Lett. **104**, 70802 (2010).
[2] C. J. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012).

Progress of the NPL Sr optical lattice clock

Elizabeth M. Bridge[1,2,*], Ian R. Hill[1,3], Yuri B. Ovchinnikov[1], Sean Donnellan[3,1],
E. Anne Curtis[1,3], and Patrick Gill[1,2,3]

1. National Physical Laboratory, Hampton Road, Teddington, UK
2. Clarendon Laboratory, University of Oxford, Parks Road, Oxford, UK
3. Blackett Laboratory, Imperial College London, Prince Consort Road, London, UK
**liz.bridge@npl.co.uk*

Frequency standards based on optical atomic transitions show great promise as next generation clocks and some have already demonstrated frequency stabilities and systematic uncertainties better than the current caesium fountain microwave primary frequencystandard [1, 2]. One prime example is the Sr optical lattice clock, which has reached fractional frequency uncertainties at the level $\sim 1 \times 10^{-16}$ in several laboratories, limited by knowledge of the black-body radition (BBR) induced frequency shift [1]. At NPL, a Sr optical lattice clock apparatus is under development with the capability to directly measure the BBR-induced frequency shift. As an initial step, we have demonstrated efficient slowing and trapping of Sr with aid of a simple permanent-magnet Zeeman slower [3]. We report on recent progress, with focus on compact narrow linewidth clock laser systems, novel BBR measurement apparatus, and characterisation of the permanent-magnet Zeeman slower.

References
[1] A. D. Ludlow et al., Science **319**, 1805 (2008).
[2] C. W. Chou et al., Phys. Rev. Lett. **104**, 070802 (2010).
[3] Yu. B. Ovchinnikov, Opt. Comm., **276**, 261 (2007).

Atomic clocks Tu-014

Lattice clock comparisons with 1×10^{-17} stability at 500 s

Travis Nicholson*, Benjamin Bloom, Jason Williams, Matthew Swallows,
Michael Martin, Michael Bishof, Sara Campbell, and Jun Ye

JILA, National Institute of Standards and Technology and the University of Colorado,
Boulder, CO, 80309-0440, USA
**nicholtl@jilau1.colorado.edu*

Optical lattice clocks based on alkaline earth atoms outperform single ion clocks [1] in measurement precision, and they have the potential to catch up with ion clocks in overall systematic uncertainty. The fractional uncertainty of our first generation strontium lattice clock has been evaluated at 1×10^{-16} [2]. To demonstrate a much smaller systematic uncertainty, we have built a second generation lattice clock based on a cavity enhanced optical lattice [3]. The large circulating power in the cavity allows us operate with a larger trap volume than a retroreflected configuration, yielding more atoms transferred into our lattice but at a lower density. Therefore, this setup both improves our signal to noise and reduces density-dependent collision shifts. Comparing our two strontium clocks, we are able to average down to the 10^{-17} level in 500 s. We report on our progress using this unprecedented stability to evaluate systematics beyond the 10^{-17} level.

References
[1] C. W. Chou *et al.*, Phys. Rev. Lett. **104**, 070802 (2010).
[2] A. D. Ludlow *et al.*, Science **319**, 1805 (2008).
[3] P. G. Westergaard *et al.*, Phys. Rev. Lett. **106**, 210801 (2011).

Generalized Ramsey excitation of an optical transition with suppressed light shift

N. Huntemann, B. Lipphardt, M. V. Okhapkin, Chr. Tamm, and E. Peik

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

We investigate an optical frequency standard based on the 467 nm electric-octupole transition $^2S_{1/2} \rightarrow {}^2F_{7/2}$ in a single trapped $^{171}Yb^+$ ion. The extraordinary features of this transition result from the long natural lifetime and from the $4f^{13}6s^2$ configuration of the upper state. The coefficients for field-induced shifts of the $^2F_{7/2}$ state are smaller than for the metastable D states in the alkaline earth ions. Recently, we have realized the unperturbed frequency of the octupole transition with a fractional uncertainty of 7.1×10^{-17} [1]. A significant contribution to this uncertainty is caused by the light shift induced by the laser driving the octupole transition. We have thereforeimplemented the generalized Ramsey excitation scheme proposed in [2] – using two pulses that are tailored in duration, frequency and phase. We demonstrate the elimination of the light shift dependence of the frequency of the central Ramsey resonance, which largely reduces the corresponding uncertainty.

References

[1] N. Huntemann *et al.*, Phys. Rev. Lett. **108**, 090801 (2012).
[2] V. I. Yudin *et al.*, Phys. Rev. A **82**, 011804 (2010).

Testing time-variation of fundamental constants using Th and U nuclear clocks

Julian Berengut, Vladimir Dzuba, and Victor Flambaum

School of Physics, University of New South Wales, Sydney NSW 2052, Australia

The low-energy (7.6 eV) transition in Th-229 could provide a reference for an optical clock of extremely high accuracy [1, 2]. Nuclear clocks would be very sensitive probes of any potential changes to the values of fundamental constants of nature [3, 4]. The 76 eV isomeric transition of U-235 has some potential advantages over the Th-229 transition, not least that its properties (energy, line width) are well known. With recent advances in high-UV frequency combs using high-harmonic generation [5] the transition may come within laser range in the foreseeable future. We present results of nuclear and atomic calculations that show a U-235 nuclear clock would have comparable accuracy to the Th-229 clock, and an absolute sensitivity to variation of fundamental constants that is larger than any other proposed laboratory reference standard.

References

[1] E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003).
[2] C. J. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012) (arXiv:1110.2490).
[3] V. V. Flambaum, Phys. Rev. Lett. **97**, 092502 (2006).
[4] J. C. Berengut *et al.*, Phys. Rev. Lett. **102**, 210801 (2009).
[5] A. Cingöz *et al.*, Nature **482**, 68 (2012).

Ultra-stable laser local oscillators

David R. Leibrandt*, Michael J. Thorpe, Chin-Wen Chou, Tara M. Fortier,
Scott A. Diddams, James C. Bergquist, and Till Rosenband

National Institute of Standards and Technology, Boulder, CO, USA
**david.leibrandt@nist.gov*

Laser frequency stabilization via spectral-hole burning has the potential to extend laser coherence beyond what is possible with Fabry-Pérot cavities. Spectral holes in $Eu^{3+}:Y_2SiO_5$ crystals are less sensitive to the thermal noise that limits optical cavities [1], and for two crystals we observe differential fractional-frequency noise below 4×10^{-17}. The absolute performance is currently limited by technical noise at an Allan deviation of 2×10^{-16} with atypical drift rate of 3×10^{-17}/s. In addition, robust spherical Fabry-Pérot cavities [2] exhibit a passive acceleration sensitivity of $2(1) \times 10^{-11}$/g, which is reduced to below 10^{-12}/g by use of active feed-forward techniques [3].

Supported by DARPA, ONR, and AFOSR.

References

[1] M. J. Thorpe *et al.*, *Frequency stabilization to 6 × 10⁻¹⁶ via spectral-hole burning*, Nat. Photonics **5**, pp. 688-693 (2011).
[2] D. R. Leibrandt *et al.*, *Spherical reference cavities for frequency stabilization of lasers in non-laboratory environments*, Opt. Express **19**, pp. 3471-3482 (2011).
[3] M. J. Thorpe *et al.*, *Measurement and real-time cancellation of vibration-induced phase noise in a cavity-stabilized laser*, Opt. Express **18**, pp. 18744-18751 (2010).

First primary frequency standard in Tunisia

Rabeb Jazy[1,*], Haikel Jelassi[1,*], Emeric de Clercq[2], Daniele Rovera[2],
Philip Tuckey[2], and Mourad Telmini[1]

1. National Centre for Nuclear Sciences and Technologies, 2020 Sidi Thabet, Tunis, Tunisia
2. LNE-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France
**jazyrabeb@yahoo.fr, haikel.jelassi@cnstn.rnrt.tn*

In this poster, we describe an optically pumped cesium-beam frequency standard (JPO) under reconstruction at the National Centre for Nuclear Science and Technology (CNSTN) in Tunisia. This prototype instrument which has been develop at laboratory "SYRTE", will be the first primary frequency standard to be implanted in Tunisia. The aim of this project is the transfer of JPO clock from SYRTE to CNSTN. It will be rebuilt in Tunisia, studied and characterized. New approaches will have to be found in order to evaluate its accuracy without having an onsite reference clock, but using comparisons by satellite. The purpose of the project is also to demonstrate the feasibility of improving the performance of the optically pumped cesium beam clock.

Precision calculation of blackbody radiation shifts for optical frequency metrology

M. S. Safronova[1,*], M. G. Kozlov[2], Z. Zuhrianda[1], and Charles W. Clark[3]

1. Department of Physics and Astronomy, University of Delaware, Newark, DE, USA
2. Petersburg Nuclear Physics Institute, Gatchina, Russia
3. Joint Quantum Institute, NIST and the University of Maryland, Gaithersburg, MD, USA
**msafrono@udel.edu*

We show that four group IIIB divalent ions, B^+, Al^+, In^+, and Tl^+ have anomalously small blackbody radiation (BBR) shifts of the $ns^2\ {}^1S_0 - nsnp\ {}^3P_0^o$ clock transitions [1, 2]. The fractional BBR shifts for these ions are at least 10 times smaller than those of any other present or proposed optical frequency standards at the same temperature. We have developed a hybrid configuration interaction + coupled-cluster method that provides accurate treatment of correlation corrections in such ions and yields a rigorous upper bound on the uncertainty of the final results. We reduce the BBR contribution to the fractional frequency uncertainty of the Al^+ clock to 4×10^{-19} at $T = 300$ K. We also reduce the uncertainties due to this effect at room temperature to 10^{-18} level for B^+ In^+, and Tl^+ to facilitate further development of these systems for metrology and quantum sensing. These uncertainties approach recent estimates of the feasible precision of currently proposed optical atomic clocks.

References

[1] M. S. Safronova, M. G. Kozlov, and Charles W. Clark, Phys. Rev. Lett **107**, 143006 (2011).
[2] Z. Zuhrianda, M. S. Safronova, and M. G. Kozlov, Phys. Rev. A **85**, 022513 (2012).

Atomic masses of calcium, strontium and ytterbium

Raman Rana[1], Martin Hoecker[2], and Edmund G. Myers[1]

1. Florida State University, Department of Physics, Tallahassee, Florida, USA
2. Max-Planck-Institut fuer Kernphysik, Heidelberg, Germany

Currently, the second most precise value for the fine structure constant is derived from "photon-recoil" measurements of *h/M* for ^{87}Rb [1] combined with the Rydberg constant, atomic transition frequencies, and the atomic masses of the electron and of ^{87}Rb [2]. An improved photon-recoil value for alpha will enable the combination of theory and experiment for the *g*-factor of the electron (which produces the most precise value for alpha), to provide an improved test of QED. Besides the alkalis, isotopes of the alkaline-earths and ytterbium make promising candidates for precise photon-recoil measurements of *h/M(atom)*. In addition, the mass of ^{40}Ca is required for obtaining the *g*-factor of hydrogen-like calcium from measurements of electron spin-flip and cyclotron frequencies of Ca^{19+}, which can be used to test bound-state QED [3]. For these and other applications, by measuring cyclotron frequency ratios of pairs of ions in a cryogenic Penning trap, we obtain the atomic masses of ^{40}Ca, $^{86,87,88}Sr$, and $^{170,171,172,173,174,176}Yb$, to a relative precision in the region of 2×10^{-10}.

References

[1] R. Bouchendira, *et al.*, Phys. Rev. Lett. **106**, 080801 (2011).
[2] B. J. Mount, M. Redshaw and E. G. Myers, Phys. Rev. A **82** 042513 (2010).
[3] S. Sturm, *et al.*, Phys. Rev. Lett. **107**, 023002 (2011).

Progress towards measuring the electron EDM with thorium monoxide

Cheong Chan[1], David DeMille[1], John M. Doyle[2], Gerald Gabrielse[2], Paul Hess[2], Nicholas R. Hutzler[2,*], Emil Kirilov[2], Brendon O'Leary[2], Elizabeth Petrik[2], and Ben Spaun[2]

1. Yale University Physics Department, New Haven, CT, USA
2. Harvard University Physics Department, Cambridge, MA, USA
**hutzler@physics.harvard.edu*

Measurement of a non-zero electric dipole moment (EDM) of the electron within a few orders of magnitude of the current best limit [1] of 1.05×10^{-27} e × cm would be an indication of CP violation beyond the Standard Model. The ACME Collaboration is searching for an electron EDM by performing a precision measurement of spin precession signals from the metastable $^3\Delta_1$ state of thorium monoxide (ThO) in a cold and slow beam. We discuss the design and completion of the first-generation apparatus, and the preliminary statistical and systematic uncertainties. We have achieved a one-sigma statistical uncertainty of 7×10^{-29} e × cm/$\sqrt{T}$, where T is the experimental running time in days, based on a data set acquired from 14 hours of running time over a period of two days.

Reference

[1] J. J. Hudson *et al.*, "Improved measurement of the shape of the electron." Nature **473**, 493 (2011).

Frequency metrology in quantum degenerate helium

Rob van Rooij[1], Joe Borbely[1], Juliette Simonet[2], Maarten Hoogerland[3], Kjeld Eikema[1], Roel Rozendaal[1], and Wim Vassen[1,*]

1. LaserLaB VU University, Amsterdam, the Netherlands
2. ENS, LKB, Paris, France
3. Department of Physics, University of Auckland, New Zealand
**w.vassen@vu.nl*

We have measured the absolute frequency of the 1557-nm doubly forbidden transition between the two metastable states of helium, $2\ ^3S_1$ (lifetime 8000 s) and $2\ ^1S_0$ (lifetime 20 ms), with 1 kHz precision [1].With an Einstein coefficient of 10^{-7} s^{-1} this is one of weakest optical transitions ever measured. The measurement was performed in a Bose-Einstein condensate of ^{4}He* as well as in a Degenerate Fermi Gas of ^{3}He*, trapped in a crossed dipole trap. From the isotope shift we deduced the nuclear charge radius difference between the α-particle and the helion. Our value differs by 4σ with a very recent result obtained on the $2\ ^3S \rightarrow 2\ ^3P$ transition [2].

References

[1] R. van Rooij, J. S. Borbely, J. Simonet, M. D. Hoogerland, K. S. E. Eikema, R. A. Roozendaal, W. Vassen, "Frequency metrology in quantum degenerate helium: Direct measurement of the $2\ ^3S_1 \rightarrow 2\ ^1S_0$ transition", Science **333**, pp. 196-198 (2011).
[2] P. Cancio Pastor, L. Consolino, G. Giusfredi, P. De Natale, M. Inguscio, V. A. Yerokhin, K. Pachucki, "Frequency metrology of helium around 1083 nm and determination of the nuclear charge radius", arXiv:1201.1362 (2012).

Frequency combs and precision spectroscopy in the extreme ultraviolet

A. Cingöz[1,*], T. K. Allison[1], D. C. Yost[1], C. Benko[1], A. Ruehl[2,3], M. E. Fermann[2], I. Hartl[2], and J. Ye[1]

1. JILA, NIST, and University of Colorado Department of Physics, Boulder, Colorado USA
2. IMRA America Inc., Ann Arbor, Michigan, USA
3. Institute for Laser, Life and Biophotonics, Vrije Universiteit, Amesterdam, The Netherlands
**acingoz@jila.colorado.edu*

We present the first direct frequency comb spectroscopy in the extreme ultraviolet (XUV) part of the spectrum by resolving transitions in atomic argon and neon at 82 and 63 nm, respectively. The XUV frequency comb is generated by frequency up conversion of a near-infrared frequency comb via intra-cavity high-harmonic generation. It is capable of delivering > 20 μW of average power per harmonic in the 50-100 nm wavelength range. The observed argon transition linewidth of 10 MHz, limited by Doppler broadening, is unprecedented in this spectral region and provides a stringent upper limit on the linewidth of individual comb teeth. The measured transition frequency of 3,655,454,073 ± 3 MHz is limited by residual Doppler shifts and provides ~10^3 times improvement over earlier measurements. We will also discuss ongoing XUV comb coherence studies via heterodyne beat of two such combs, which will provide a new paradigm for high precision tests and spectroscopy in the XUV.

References

[1] A. Cingöz *et al.*, "Direct Frequency Comb Spectroscopy in the Extreme Ultraviolet", Nature **482**, pp. 68-71 (2012).
[2] T. K. Allison *et al.*, "Extreme Nonlinear Optics in a Femtosecond Enhancement Cavity", PRL **107**, pp. 183903-183908 (2011).

Search for an electron EDM with trapped hafnium fluoride ions

Huanqian Loh[1,*], Kang-Kuen Ni[1], Kevin Cossel[1], Matt Grau[1], Daniel Gresh[1], Robert W. Field[2], Jun Ye[1], and Eric A. Cornell[1]

1. JILA, NIST and University of Colorado (Boulder), and Department of Physics, University of Colorado (Boulder), USA
2. Department of Chemistry, Massachusetts Institute of Technology
**loh@jilau1.colorado.edu*

The precision measurement of an electron electric dipole moment (eEDM) is an experiment that tests fundamental symmetries and physics beyond the Standard Model [1]. Trapped hafnium fluoride molecular ions in the $^3\Delta_1$ metastable electronic state are suitable candidates for an eEDM search due to their large effective electric fields and long electron spin coherence times [2]. To create HfF^+ in the desired quantum state, we first use two optical photons to excite a supersonic beam of neutral HfF molecules to a Rydberg state, which then autoionizes into predominantly a single rovibrational level of HfF^+ in its ground $^1\Sigma^+$ state. The autoionized HfF^+ in the ground state can then be transferred to the $^3\Delta_1$ state using transitions that have been recently identified. We report progress towards an eEDM measurement on several fronts: the mapping out of energy levels of HfF^+ up to 15000 cm^{-1} using velocity modulation spectroscopy, which leads to the identification of promising transitions to the $^3\Delta_1$ state; the loading and trapping of ions in a novel radiofrequency Paul trap optimized for collection of fluorescence photons and field uniformity; the reading out of ion states using laser-induced fluorescence in the ion trap; the search for more efficient state readout systems beyond laser-induced fluorescence. This work is funded by the National Science Foundation and the Marsico Endowed Chair.

References

[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, and E. A. Hinds, *Improved measurement of the shape of the electron*, Nature **473**, pp. 493-496 (2011).
[2] A. E. Leanhardt, J. L. Bohn, H. Loh, P. Maletinsky, E. R. Meyer, L. C. Sinclair, R. P. Stutz, and E. A. Cornell, *High-resolution spectroscopy on trapped molecular ions in rotating electric fields: A new approach for measuring the electron electric dipole moment*, J. Mol. Spectrosc. **270**, pp. 1-25 (2011).

A nuclear-electronic spin gyro-comagnetometer

G. Renon[1,*], N. Zahzam[1], Y. Bidel[1], A. Bresson[1], and P. J. Nacher[2]

1. DMPH, ONERA The French Aerospace Lab, Palaiseau, France
2. Laboratoire Kastler Brossel, ENS, CNRS, UPMC, Paris France
**geoffrey.renon@onera.fr*

We are presently starting a project aiming to fully characterize a new generation of atomic gyroscope based on the detection of a nuclear spin orientation with an alkali magnetometer [1]. The key element of the device is a spherical gas cell heated at about 170°C and shielded from parasite magnetic fields. This cell is filled with an alkali gas (Rb, K…) with an electronic spin and a noble gas (^{3}He, ^{21}Ne, ^{129}Xe…) with a nuclear spin. The noble gas is polarized by Spin Exchange Optical Pumping (SEOP). In addition, the magnetic field created by the nuclear magnetization is canceled with a homogeneous magnetic field. Alkali atoms feel no magnetic field and evolve in a collisional regime (Spin Exchange Relaxation Free – SERF) allowing the realization of an ultra sensitive in situ alkali magnetometer [2] which detects the nuclear spin dynamic and then gives us a rotation measurement of the system. Our project deals with the conception, realization and characterization of this nuclear-electronic spin gyroscope very promising for applications requiring miniature sensors with a high performance.

References

[1] T. W. Kornack, R. K. Ghosh, and M. V. Romalis, "Nuclear Spin Gyroscope Based on an Atomic Comagnetoter", PRL, vol. **95**, 230801, 2005.
[2] I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer", Nature, vol. **422**, p. 596-599, 2003.

Accurate measurement and control of an IR laser frequency using an optical frequency comb and a remote frequency reference

B. Chanteau[1,*], O. Lopez[1], W. Zhang[2], G. Santarelli[2], Y. Le Coq[2], F. Auguste[1], B. Darquié[1], C. Chardonnet[1], and A. Amy-Klein[1]

1. Laboratoire de Physique des Lasers, CNRS and Université Paris 13, Villetaneuse, France
2. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, Paris
**bruno.chanteau@univ-paris13.fr*

Ultra-high-resolution spectroscopy enables to test fundamental physics with molecules such as parity non conservation 0 or the stability of the electron-to-proton mass ratio 0. It is thus very challenging to develop an ultrastable frequency stabilization scheme in the mid-IR region where molecules exhibit rovibrational transitions. We have built a frequency chain which enables to measure the absolute frequency of a CO_2 laser emitting around 10 µm and stabilized onto a molecular absorption line. The set-up uses an optical frequency comb with sum-frequency generation. The frequency reference is an ultrastable 1.55 µm laser, transferred from SYRTE to LPL by an optical link [3]. We are now progressing towards the frequency stabilization of the IR laser via the frequency comb and the extension of this technique to quantum cascade lasers for a larger spectral range.

References

[1]. B. Darquié *et al.*, Chirality 22, pp. 870-884 (2010).
[2]. A. Shelkovnikov *et al.*, Phys. Rev. Lett. 100, p. 150801-150803 (2008).
[3]. O. Lopez *et al.*, Opt. Expr. 18, p. 16849-16857 (2010).

Fundamental physics tests using the LNE-SYRTE clock ensemble

Jocelyne Guéna[1,*], Michel Abgrall[1], Daniele Rovera[1], Peter Rosenbusch[1], Michael Tobar[2], Philippe Laurent[1], André Clairon[1], and Sébastien Bize[1]

1. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 75014 Paris, France
2. The University of Western Australia, Crawley, 6009, WA Australia
**jocelyne.guena@obspm.fr*

SYRTE is developing an ensemble of high performance atomic clocks comprising 3 laser-cooled atomic fountain clocks [1], 3 optical lattice clocks and ultra stable microwave and optical oscillators. Such an ensemble provides many possibilities for testing fundamental physical laws, relying on the high accuracy and stability of these devices. We report more specifically on comparisons between the ^{87}Rb and ^{133}Cs ground state hyperfine frequencies using the fountains. The measurements over 14 years set a stringent limit to a possible variation with time, and also with gravitational potential, of the Rb/Cs hyperfine frequency ratio. A notable advance in this work was the simultaneous operation with Rb and Cs in one fountain [2]. Combining with other available highly accurate clock comparisons, we provide independent constraints on today time variations and couplings to gravity of the 3 constants: fine structure constant α, scaled quark mass m_q / Λ_{QCD}, and electron-to-proton mass ratio m_e / m_p.

References

[1] J. Guéna *et al.*, *Progress on Atomic Fountains at LNE-SYRTE*, IEEE Trans. on Ultrason. Ferroelectr. and Freq. Control **59**, pp. 391-410 (2012); arXiv:1204.3621v1.
[2] J. Guéna *et al.*, *Demonstration of a Dual Alkali Rb/Cs Fountain Clock*, IEEE Trans. on Ultrason. Ferroelectr. and Freq. Control **57**, no.3, pp. 647-653 (2010).

Optical transitions in highly charged ions for atomic clocks with enhanced sensitivity to variation of fundamental constants

Julian Berengut, Vladimir Dzuba, Victor Flambaum, and Andrew Ong

School of Physics, University of New South Wales, Sydney NSW 2052, Australia

Optical transitions can occur in some highly charged ions (HCIs) when the ion stage and nuclear charge are tuned such that orbitals with different principal quantum number and angular momentum are nearly degenerate [1]. In these cases thetransition energy may be within laser range even though the ionisation energy is large (of order several hundred eV). We have identified several such systems and shown that they have a number of properties that could make them suitable for atomic clocks with high accuracy. Strong E1 transitions provide options for laser cooling and trapping, while narrow transitions can be used for high-precision spectroscopy and tests of fundamental physics. In particular we found transitions that would have the highestsensitivity to variation of the fine-structure constant ever seen in atomic systems [2, 3]. HCI clocks utilising these transitions could confirm the indications of a spatial gradient in the fine-structure constant observed in quasar absorption spectra data [4, 5].

References

[1] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, Phys. Rev. Lett. **105**, 120801 (2010).
[2] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, A. Ong, Phys. Rev. Lett. **106**, 210802 (2011).
[3] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, A. Ong, arXiv:1204.0603 (2012).
[4] J. K. Webb *et al.*, Phys. Rev. Lett. **107**, 191101 (2011).
[5] J. C. Berengut and V. V. Flambaum, Europhys. Lett. **97**, 20006 (2012).

Leggett-Garg inequalities for atom interferometry

Qiongyi He, Peter Drummond, and Margaret Reid*

CAOUS Centre for Atom Optics, Swinburne University of Technology, Melbourne, Australia
**mdreid@swin.edu.au*

We construct generalisations of Leggett-Garg (LG) inequalities [1] that test realism (R) and non-invasive measurability (NIM) in multi-particle scenarios not limited to two outcomes. The inequalities provide a means to quantify the level of realism and NIM being tested – from micro, though to meso and, ultimately, macro – with the inclusion of parameters S and δ that denote the size of reality and noninvasiveness of measurement, in terms of particle number. We show how these LG inequalities are predicted to be violated by dynamical correlated systems, as might be realised using double-potential well Bose-Einstein condensates, and atom interferometers [2]. The measured output of a Mach-Zehnder interferometer can reveal violations of these inequalities, and be used to falsify classical trajectories for particle paths. We analyse three different strategies to realise the NIM: measure-and-regenerate, ideal-negative result, and weak quantum nondemolition QND number measurements [3].

References

[1] A. J. Leggett and A. Garg, *Quantum Mechanics versus Macroscopic realism: Is the flux there when nobody looks?*, Phys. Rev. Lett. **54**, pp. 857-860 (1985).
[2] C. Gross *et al.*, *Nonlinear atom interferometer surpasses classical precision limit*, Nature **464**, pp. 1165-1169 (2010).
[3] M. E. Goggin *et al.*, *Violation of the Leggett-Garg inequality with weak measurements of photons* Proc. Natl. Acad. Sci. **108**, pp. 1256-1261 (2011).

Precision measurements… Tu-030

A new search for tensor currents in the weak decay of magneto-optically trapped ^{6}He

David Zumwalt for the ^{6}He collaboration

University of Washington, Seattle, Washington
dwz@uw.edu

The beta decay of ^{6}He presents a unique opportunity to search for new physics. Determining the correlation between the electron and the anti-neutrino allows searching for tensor currents predicted by extensions of the Standard Model. Because the neutrino cannot be detected with high efficiency, ^{6}He is ideal for this search because it is a light nucleus and yields a recoiling ^{6}Li ion with sufficient energy to be detected. In coincidence with the beta, measuring the ^{6}Li ion allows kinematic reconstruction of the neutrino momentum. Up to the present the precision has been limited due to either low number of ^{6}He atoms (nuclear half-life < 1 second) or interactions of the ^{6}Li ions with the environment. To overcome these limitations we have developed the most intense source of ^{6}He in the world [1] and we have set up a MOT. We have succeeded in trapping 30 atoms already. We also developed an original method, using an additional cycling transition, which allows detection of a few atoms in spite of the unavoidable light scattering from the intense trap lasers. Results will be presented.

Reference

[1] A. Knecht *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **660**, 43 (2011).

Towards packaged micro-integrated semiconductor laser modules for the deployment of cold atom based quantum sensors in space

Ahmad Bawamia[1,*], Anja Kohfeldt[1], Max Schiemangk[2], Erdenetsetseg Luvsandamdin[1], Christian Kuerbis[1], Stefan Spiessberger[1], Alexander Sahm[1], Andreas Wicht[1], Goetz Erbert[1], Achim Peters[1, 2], and Guenther Tränkle[1]

1. Ferdinand-Braun Institut, Leibniz-Institut fuer Hoechstfrequenztechnik, Berlin, Germany
2. Humboldt-Universitaet zu Berlin, Germany
**ahmad.bawamia@fbh-berlin.de*

We report on the development of very robust, energy efficient, micro-integrated Master-Oscillator-Power-Amplifier (MOPA) and Extended Cavity Diode Laser (ECDL) modules for the deployment of cold atom based quantum sensors in space. They fit on micro optical benches not larger than 80 × 25 mm^2 and make use of either already space qualified or space qualifiable components and integration technologies. With MOPAs and ECDLs designed for Rubidium BEC and atom interferometry experiments at 780 nm we achieved an intrinsic linewidth of 190 kHz at 1 W and of 300 Hz at 35 mW, respectively. The MOPA module has been successfully vibration tested up to 8 g_{RMS} random noise, and micro-integrated modules based for 1060 nm that are based on the same integration technology have successfully passed vibration tests up to 29 g_{RMS} and 1500 g pyro-shock. Further, we outline the next steps in diode laser system micro-integration that combine the MOPA and ECDL concepts with micro-integrated fibre-coupling in a hermetic housing that allows for space deployment. These concepts can be transferred to other wavelengths.

Precision spectroscopy of the 2S-4P transition in atomic hydrogen

Axel Beyer[1,*], Arthur Matveev[1], Christian G. Parthey[1], Janis Alnis[1], Nikolai Kolachevsky[1], Thomas Udem[1], and Theodor W. Hänsch[1,2]

1. Max Planck Institute of Quantum Optics, 85748 Garching
2. Ludwig Maximilian University, 80799 Munich
**Axel.Beyer@mpq.mpg.de*

The comparison between measured and calculated transition frequencies in atomic hydrogen can provide stringent tests of bound state QED. For the last decade, this comparison has been limited by the proton charge radius determined by electron-proton scattering. Recently, laser spectroscopy of muonic hydrogen provided a value, which is ten times more accurate than any previous measurement [1]. But this value differs from the CODATA 2010 value, obtained by a global adjustment of fundamental constants using data from electron-proton scattering and hydrogen experiments for the proton charge radius, by seven standard deviations [2]. The muonic hydrogen result led to a comprehensive search for the cause of this discrepancy, but no convincing argument could be found so far. Because the current CODATA value is mainly based on observations in atomic hydrogen, transition frequency measurements with improved accuracy can help to solve this puzzle or at least to rule out hydrogen experiments asa possible source for the discrepancy. Here we report on the setup which has been developed for the measurement of the one-photon $2S_{1/2}$-$4P_{1/2}$ transition frequency and discuss our preliminary results.

References

[1] Pohl *et al.*, *The size of the proton*, Nature **466** (7303), 2010.
[2] Mohr *et al.*, *CODATA 2010*, arXiv:1203.5425.

Recent measurements of 1S-2S transition frequency in atomic hydrogen

N. Kolachevsky[1,*], A. Matveev[1], C. G. Parthey[1], K. Predehl[1], J. Alnis[1], A. Beyer[1], R. Holzwarth[1], Th. Udem[1], T. Wilken[1], M. Abgrall[2], D. Rovera[2], Ch. Salomon[2], P. Laurent[2], G. Grosche[3], Th. Legero[3], H. Schnatz[3], S. Weyers[3], B. Altschul[4], and T. W. Hänsch[1]

1. Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
2. LNE-SYRTE, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France
3. Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
4. University of South Carolina, Columbia, South Carolina 29208, USA
**kolik@lebedev.ru*

We report on two recent precision measurements of 1S-2S transition frequency in atomic hydrogen. The first done in May 2011 against the LNE-SYRTE transportable cesium fountain clock FOM has shown a fractional uncertainty of 4.2×10^{-15} [1], 3.3 times better than for the previous result from 2003. The second measurement was performed in November 2011 using distant CSF1 fountain clock at PTB, Braunschweig. To compare frequencies we used a 900 km long actively stabilized fiber link. The link allows to measure the frequency of a transfer Er-doped cw fiber laser running at MPQ against CSF1. By comparison of two most recent results for the hydrogen 1S-2S transition frequency we can constrain the linear combination of Lorentz boost symmetry violation parameters in the SME framework.

Reference

[1] C. G. Parthey *et al.*, Phys. Rev. Lett. **107**, 203001 (2011).

Strontium atoms in optical lattices: applications to optical clocks and accurate gravimeters

N. Poli[1,*], M. G. Tarallo[1], F.-Y. Wang[1], M. Schioppo[1], D. Sutyrin[1], M. Prevedelli[2], and G. M. Tino[1]

1. Dipartimento di Fisica e Astronomia and LENS, Istituto Nazionale Fisica Nucleare, Polo scientifico – Università di Firenze, Via Sansone, 1 - Sesto Fiorentino 50019, Italy
2. Dipartimento di Fisica - Università di Bologna Via Irnerio 46, 40126 Bologna, Italy
**nicola.poli@unifi.it*

I will present the most recent precision measurements done with ultracold strontium atoms trapped in optical lattices. While fermionic ^{87}Sr atoms have been considered a good candidate for future optical clocks aiming to 10^{-17} relative accuracy or below [1], we concentrated on accurate measurements of gravity with the most abundant ^{88}Sr bosonic isotope. The long coherence time in Bloch oscillation exploited with ^{88}Sr trapped in vertical optical lattice, allow to observe more than 10^4 Bloch oscillations with a resulting resolution of 10^{-7} in gravity measurements, with no fundamental limit to reduce the resolution by another order of magnitude. Detailed study of systematic effects and a comparison with a classical FG5 gravimeter will be presented [2]. Furthermore, I will present the status of the recent developed compact and transportable version of a strontium optical lattice clock [3] and the prospect toward optical frequency comparisons with primary frequency standards in Italy.

References

[1] A. D. Ludlow *et al.*, Science **319**, 1805 (2008).
[2] N. Poli, *et al.*, Phys. Rev. Lett. **106**, 038501 (2011).
[3] M. Schioppo *et al.*, Proceedings of EFTF 2010 (2010).

Enhanced electron EDM $\mathcal{P},\mathcal{T}$-odd constant obtained from highly-correlated molecular four-component configuration interaction calculations

Timo Fleig[1] and Malaya K. Nayak[2]

1. Laboratoire de Chimie et Physique Quantiques, IRSAMC, Université Paul Sabatier, Toulouse, France
2. Bhabha Atomic Research Centre, Trombay, Mumbai - 400085, India

The current upper limit on the electron electric dipole moment (EDM) is $|d_e| < 10.5 \times 10^{-28} e$ cm [1], from measurements on YbF. Due to their strong internal electric fields, polar diatomic molecules in general are interesting candidates in the search for the electron EDM, the discovery of which would significantly constrain proposed extensions to the Standard Model of particle physics [2].

We have implemented the evaluation of the electron EDM Hamiltonian operator as an expectation value over four-component molecular Dirac wavefunctions including the contributions of dynamic electron correlation. The electronic-structure programs used in this approach are the `KR-CI` module [3] of the `DIRAC10` program package. In initial applications we show the importance of dynamic electron correlation effects on the $\mathcal{P},\mathcal{T}$-odd interaction constant W_d in the IH^+ molecular ion, a possible candidate [4] in the search for the electron EDM.

References
[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, *et al.*, *Nature* **473** (2012) *493*.
[2] E. D. Commins, *Adv. Mol. Opt. Phys.* **40** (1999) *1*.
[3] S. Knecht, H. J. Å. Jensen, T. Fleig, *J. Chem. Phys.* **132** (2010) *014108*.
[4] T. A. Isaev, A. N. Petrov, N. S. Mosyagin, A. V. Titov, *Phys. Rev. Lett.* **95** (2005) *163004-1*.

Regularities and tendencies in atomic spectra

Jean-Christophe Pain

CEA, DAM, DIF, F-91297 Arpajon, France
jean-christophe.pain@cea.fr

Historically, the use of statistical methods for the description of complex quantum systems was primarily motivated by the failure of a line-by-line interpretation of atomic spectra. Such methods reveal regularities and tendencies in the distributions of levels and lines. Up to now, much attention was paid to the distribution of energy levels (Wigner surmise, random-matrix model...). However, information about the distribution of the lines (energy and strength) is lacking. Thirty years ago, Learner found empirically an unexpected law: the logarithm of the number of lines whose intensities lie between $2^k I_0$ and $2^{k+1} I_0$, I_0 being a reference intensity and k an integer, is a decreasing linear function of k [1, 2]. In this work, the fractal nature of such an intriguing regularity is outlined and a calculation of its fractal dimension is proposed. Other properties which remain unexplained are also presented, such as the role of quantum chaos or the fact that the distribution of line strengths follows Benford's law of anomalous numbers [3].

References
[1] R. C. M. Learner, *A simple (and unexpected) experimental law relating to the number of weak lines in a complex spectrum*, J. Phys. B **15**, pp. L891-L895 (1982).
[2] C. Bauche-Arnoult and J. Bauche, *Comparison of atomic data modeling with experimental intensities*, J. Quant. Spectrosc. Radiat. Transfer **58**, pp. 441-447 (1997).
[3] J.-C. Pain, *Benford's law and complex atomic spectra*, Phys. Rev. E , 012102 (2008).

Laser spectroscopy of the radioactive La isotopes

H. Iimura[1], F. Buchinger[2], and H. A. Schuessler[3,*]

1. Japan Atomic Energy Agency, Tokai Mura, Japan
2. Department of Physics, McGill University, Montreal, Canada
3. Department of Physics, Texas A&M University,College Station,TX 77843-4242, USA
**schuessler@physics.tamu.edu*

We have used collinear laser spectroscopy to measure on-line nuclear moments and charge distributions of many short lived isotopes. Experiments were done at ISAC, JAEA , and Riken. Nuclei are known to have spherical, prolate, oblate and exotic octopole shapes. All of these are rotationally symmetrical. We have further evaluated our data and confirm that the neutron deficient isotopes $^{129\text{-}135}$La show a rare none rotationally symmetrical triaxial shape in their ground states. That means their masses are distributed unequally along the three axes of length, width and height. This feature is reflected in the hyperfine structure (HFS) spectrum of a suitably chosen valence electron. By measuring the nuclear moments (μ and Q) the onset and decline of this unusual shape is investigated on the chain of neutron deficient La isotopes. This work was supported in part by the Robert A. Welch Foundation (grant No. A1546).

Spectroscopy Tu-038

Optically detected magnetic resonance using elliptical polarization

Kazuki Fujita, Shuya Taniguchi, Ichiro Yoshida, Yoshitaka Hoshina,
and Masaharu Mitsunaga*

Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan
**mitunaga@sci.kumamoto-u.ac.jp*

We present theoretical and experimental results on optically detected magnetic resonance (ODMR) signals in the $3S_{1/2}$-$3P_{1/2}$, $D1$ transition of a hot Na atomic vapor [1], particularly focusing on the dependence of the ODMR signals on the incident light polarization. We have found that, while circular polarization gives the largest ODMR signal for the Zeeman end-resonances including ($F = 2$, $m_F = \pm 2$ levels, elliptical polarization is much more favorable for the observation of the inner Zeeman transitions. Detailed theoretical analysis based upon the rate equations including all the Zeeman sublevels is presented. Experimentally, the nuclear Zeeman splitting has been observed by using elliptical polarization. Satisfactory agreement has been obtained between theoretical simulations and experimental results.

Reference

[1] K. Motomura and M. Mitsunaga, *High-resolution spectroscopy of hyperfine Zeeman components of the sodium D_1 line by coherent population trapping*, J. Opt. Soc. Am. **B19**, pp. 2456-2460 (2002).

Velocity selective polarization spectroscopy of an atomic Rb vapor in lambda and ladder excitation schemes

Jesús Flores-Mijangos, Fernando Ramírez-Martínez, Cristian Mojica-Casique, and José Jiménez-Mier

Instituto de Ciencias Nucleares, UNAM, Circuito Exterior, Ciudad Universitaria, 04510 México, D.F., México
**ferama@nucleares.unam.mx*

We present both theoretical and experimental results for the absorption of a linearly polarized weak probe laser beam locked to an hyperfine transition in the rubidium D_2 line while the frequency of a circularly polarized pump beam, either co- or counter-propagating with the probe beam, is scanned either across the same manifold or through the $5P \rightarrow 5D$ transition. Using balanced detection, we recorded separately variations in the intensities of the two mutually orthogonal linearly polarized components of the probe beam, which corresponds to measuring the birefringence induced on the atomic vapor by the pump beam. In both co- and counter-propagating cases we clearly obtained defined absorption and polarization atomic signals, as well as cross-over resonances. Numerical calculations based on rate equations allowed us to determine the population differences between the 5*S* and 5*P* magnetic sublevels in Rb. With these results we calculated the changes of the absorption coefficients for right and left circularly polarized light as functions of the pump light frequency and intensity obtaining excellent agreement with experimental spectra. These results were applied to the development of modulation-free laser frequency stabilization techniques.

Electromagnetically induced polarization rotation in Na ladder systems

Yoshitaka Hoshina, Shuya Taniguchi, Kazuki Fujita, Ichiro Yoshida, and Masaharu Mitsunaga*

Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan
**mitunaga@sci.kumamoto-u.ac.jp*

We have observed electromagnetically induced polarization rotation (EIPR) in the $3S_{1/2}$-$3P_{1/2}$-$4D_{3/2}$ and $3S_{1/2}$-$3P_{3/2}$-$4D_{3/2,5/2}$ three-level ladder systems in a hot Na vapor [1]. In the presence of a strong circularly-polarized coupling beam resonant to the upper ladder transition, the polarization angle of a probe beam, resonant to the lower ladder transition, was rotated by up to 18 degrees. The EIPR spectra exhibited a unique double-dispersion feature, which was related to the EIT (electromagnetically induced transparency)-circular dichroism spectra by the Kramers-Kronig relations and was more pronounced for the higher coupling powers. The optical switch experiment based on EIPR gave a fast response of less than 100 ns.

Reference

[1] N. Hayashi, A. Fujisawa, H. Kido, K. Takahashi, and M. Mitsunaga, *Interference between electromagnetically induced transparency and two-step excitation in three-level ladder systems*, J. Opt. Soc. Am. **B27**, pp. 1645-1650 (2010).

A frequency-comb-referenced OPO for sub-Doppler spectroscopy

I. Ricciardi[1], E. De Tommasi[1], P. Maddaloni[1], S. Mosca[1], A. Rocco[1], J.-J. Zondy[2], M. De Rosa[1,*], and P. De Natale[3]

1. CNR–INO, Istituto Nazionale di Ottica, and LENS, Pozzuoli (NA), Italy
2. Laboratoire Commun de Métrologie LNE-CNAM, La Plaine Saint-Denis, France
3. CNR–INO, Istituto Nazionale di Ottica, and LENS, Firenze, Italy
**maurizio.derosa@ino.it*

We present a singly-resonant, 1064-nm-pumped, cw optical parametric oscillator (OPO), emitting more than 1 W between 2.7 and 4.2 μm, specifically designed for high-resolution and precise spectroscopy in the mid-infrared region. Both pump and signal are frequency stabilized to a near-infrared optical frequency comb, referenced to the Cs primary time standard. A fractional Allan deviation of $\sim 3 \times 10^{-12}\ \tau^{-1/2}$ has been estimated between 1 and 200 s. As a test, we carried out sub-Doppler spectroscopy of rovibrational transitions of CH_3I around 3.4 μm, resolving their electronic quadrupole hyperfine structure, estimating an OPO linewidth lower than 200 kHz (FWHM), and determining absolute frequencies with a statistical uncertainty of 50 kHz [1]. The availability of such a precise and powerful source is of primary interest for spectroscopic studies of subtle effects, tests of fundamental theories, or optical manipulation of molecules.

Reference
[1] I. Ricciardi *et al.*, *A frequency-comb-referenced singly-resonant OPO for sub-Doppler spectroscopy*, Optics Express **20**, 9178–9186 (2012).

Realtime software-base frequency control for two diode lasers

Cristian Mojica-Casique*, Jesus Flores-Mijangos, Fernando Ramírez-Martínez, and Jose Jiménez-Mier

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
**xtianadan@gmail.com*

This work presents the design and implementation of a LabView based system for controlling and stabilizing the frequency of extended cavity diode lasers. The system was developed for creating a magneto-optical trap for rubidium atoms. Hence, our system automatically scans the frequency of our lasers across the D_2 line and then locks it to any of the transitions or crossovers in the manifold. A polarization spectroscopy apparatus [1] is used to generate a dispersion signal to feedback the laser after a simple PID algorithm implemented entirely within LabView. The lock bandwidth is ~ 2 MHz. Currently, we are capable of controlling two lasers simultaneously and independently. An additional advantage is that the locking point over the transition spectrum can be controlled in realtime while the laser frequency remains locked. Although the system was developed for a magneto-optic trap experiment, it can be used in a wide variety of control applications.

Reference
[1] C. P. Pearman, *Polarization spectroscopy of a closed atomic transition: applications to laser frequency locking*, J. Phys. B: At. Mol. Opt. Phys. **35**, pp. 5141-5151 (2002).

Raman tweezers spectroscopy of supercooled water droplet

Maki Tachikawa*, Azusa Muraoka, Hidenori Suzuki, and Yoshiki Matsuzaki

Department of Physics, Meiji Universiry, Kawasaki City, Kanagawa, Japan
**tachikaw@isc.meiji.ac.jp*

Supercooled water exhibits unique physical properties such as a negative thermal expansion and the thermodynamic singularity around -45 °C. Although it is generally accepted that hydrogen bonding between water molecules is responsible for the properties, their detailed mechanism is not well understood. We probe thermodynamic anomalies of liquid water in highly supercooled state by use of optical trapping and Raman spectroscopy. Micron-sized drops of purified water are levitated in air and cooled down to -35 °C free from contact freezing. Stokes photons are scatterred from water molecules excited by the trapping radiation. An enthalpy change due to hydrogen-bond breaking is derived from temperature dependence of the Raman spectral profile in the OH stretching band. The isobaric heat capacity calculated from the enthalpy data shows an anomalous increase as the temperatures approaches -45 °C, suggesting the existence of the second critical point [1].

Reference

[1] P. H. Poole, F. Sciortino, U. Essmann, H. E. Stanley, Nature **360**, 324 (1992).

Dielectronic recombination of low-ionized tungsten ions

U. I. Safronova[1,*], A. S. Safronova[1], and P. Beiersdorfer[2]

1. Physics Department, University of Nevada, Reno, NV 89557, USA
2. Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
**ulyanas@unr.edu*

Our recent work on theoretical studies of dielectronic recombination of W ions focuses first on highly ionized [1] and now on low-ionized W ions [2]. In particular, energy levels, radiative transition probabilities, and autoionization rates for [Cd] $4f^{14}5p^{6}5l'nl$, [Cd] $4f^{14}5p^{6}6l''nl$, [Cd] $4f^{14}5p^{5}5d^{2}nl$, [Cd] $4f^{14}5p^{5}5d6l''nl$, [Cd] $4f^{13}5p^{6}5d^{2}nl$, and [Cd] $4f^{13}5p^{6}5d6l''nl$ ($l' = d, f, g$, $l'' = s, p, d$, $l = s - g$, and $n = 5 - 7$) states of Yb-like tungsten (W^{4+}) are calculated and compared using the relativistic many-body perturbation theory method (RMBPT code), the Multiconfiguration relativistic Hebrew University Lawrence Livermore Atomic Code (HULLAC code), and the Hartree-Fock-Relativistic method (COWAN code). It allows to critically evaluate recommended atomic data for their accuracy. Synthetic dielectronic satellite spectra are simulated in a broad spectral range from 200 to 1400 Å. This research was supported by DOE under OFES grant DE-FG02-08ER54951.

References

[1] U. I. Safronova, A. S. Safronova, P. Beiersdorfer *Excitation energies, radiative and autoionization rates, dielectronic satellite lines and dielectronic recombination rates for excited states of Mg-like W from Na-like W*, J. Phys. B **42**, pp. 165010 (2009).
[2] U. I. Safronova, A. S. Safronova *Dielectronic recombination of Er-like tungsten*, Phys. Rev. A **85**, 032507 (2012).

Elastic constants of hcp ^{4}He through of path integral Monte Carlo

Luis A. Peña Ardila[1,2,*], Silvio A. Vitiello[2], and Maurice De Koning[2]

1. Bose Einstein Condensation and CNR Group, Università di Trento, Trento, Italy
2. Universidade Estadual De Canpinas, Campinas, São Pablo, Brazil
**ardila@science.unitn.it*

Through of Path Integral Monte Carlo method (PIMC) we determine the elastic constants of solid ^{4}He in its hcp phase. These elastic properties are very important in view of their apparent involvement in the phenomenon of supersolidity in solid ^{4}He. The stiffness coefficients are obtained by imposing different distortions to a periodic cell containing 180 atoms, followed by measurement of the elements of the corresponding stress tensor. For this purpose an appropriate path-integral expression for the stress tensor observable is derived and implemented into the PIMC++ package. A comparison of the results to available experimental data shows an overall good agreement of the density dependence of the elastic constants, with the single exception of C_{13}.

Reference

[1] Luis Aldemar Peña Ardila, Silvio A. Vitiello, and Maurice de Koning, " Elastic Constants of hcp ^{4}He: Path Integral Monte Carlo Vs. Experiment", Phys. Rev. B **84**, 094119 (2011) [6 pages].

Observation of topologically stable 2D skyrmions in an antiferromagnetic spinor Bose-Einstein condensate

J. Choi, W. J. Kwon, S. W. Seo, M. Kim, M. Lee, and Y. Shin*

Department of Physics and Astronomy, Seoul National University, Seoul, South Korea
**yishin@snu.ac.kr*

We observed the two-dimensional skyrmion excitations and its time-dependent phenomenon in quasi-2D polar Bose-Einstein condensate of F=1 23Na atoms, where 2D skyrmion is topologically protected. [1] Spin rotation method was used to imprint skyrmion spin textures on the condensate. The skyrmion was stable about tens of ms, but decayed to a uniform spin texture after all. The collapse of the skyrmion indicates that the polar phase inside the condensate is being broken during time evolution without topological charge density flow from the outside of the finite size condensate. We suggest the possible formation of Half-quantum vortices in the collapse process

Reference

[1] J. Choi, W. J. Kwon and Y. Shin, Physical Review Letters **108**, 035301(2012).

Vortex lattices in two-species Bose-Einstein condensates

Pekko Kuopanportti[1,*], Jukka A. M. Huhtamäki[1], and Mikko Möttönen[1,2]

1. Department of Applied Physics/COMP, Aalto University, P. O. Box 13500, FI-00067 Aalto, Finland
2. Low Temperature Laboratory, Aalto University, P. O. Box 13500, FI-00067 Aalto, Finland
**pekko.kuopanportti@aalto.fi*

One of the most remarkable characteristics of a Bose–Einstein condensate is that it responds to rotation by forming quantized vortices. In this theoretical work, we investigate vortex lattices in a rotating two-component condensate in which the components have unequal atomic masses and interact attractively with each other [1]. We show that when the ratio of the atomic masses is suitable and the intercomponent attraction is sufficiently strong, the system exhibits unconventional ground-state vortex structures in a harmonic trap, such as lattices having a square geometry or consisting of two-quantum vortices. The exotic lattices can be understood in terms of the Feynman relation, which states that the vortex density is proportionalto the atomic mass, and they should be realizable with current experimental techniques.

Reference

[1] P. Kuopanportti, J. A. M. Huhtamäki, and M. Möttönen, Phys. Rev. A **85**, 043613 (2012).

Two mode at Bose-Einstein Condensate in triple well

E. L. Lapolli[1,*] and F. F. de Souza Cruz[2]

1. CCT - Departamento de Fisica, Universidade Estadual de Santa Catarina,
Joinville, SC, 89219-710, Brasil
2. Departamento de Fisica, Universidade Federal de Santa Catarina, Florianopolis, SC, 88040-900, Brasil
**lapollifsc@yahoo.com.br*

In this work we investigate the dynamics of a system constituted by Bose-Einsten condensate in three well in line [1, 2]. This system presents among its collectives modes, a behavior of two-mode called twin mode [3, 4].The twin modes are generated over specific initial conditions and only in this mode there are not chaos when we change the interaction parameters.

We used the semi-classical Hamiltonian form obtained by three modes through the coherent state transformation based in the su(3) algebra [5]. We analyzed a way to obtain a hamiltonian semi-classical two-mode [6] by canonical transformation from semi-classical three-mode model.

References

[1] S. Mossmann and C. J. Jung, Phys. Rev. A **74** 033601 (2006).
[2] F. Trimborn, D. Witthaut, and H. J. Korsch, Phys. Rev. A **79**, 013608 (2009).
[3] Thiago F. Viscondi, K. Furuya, and M. C. de Oliveira, Euro. Phys. Lett. **90**,10014 (2010).
[4] Thiago F. Viscondi and K. Furuya, J. Phys. A: Math. Theor. **44** 175301 (2011).
[5] Frederico Firmo de Souza Cruz, Tese: *Teorias Microscópicas para Movinentos Coletivos de Grande Amplitude*., Doutorado, Universidade de São Paulo, São Paulo, 1986.
[6] A. Smerzi, S. Fantoni, S. Giovannazi and S. R. Shenoy, Phys. Rev. Lett. A **79**, 4950 (1997).

Unlock the mystery of near-resonance Bose gases

Fei Zhou

Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada
**feizhou@phas.ubc.com*

The properties of quantum gases beyond the usual dilute limit have been one of the most challenging topics in the field of quantum many-body physics. In this talk, I am going to report the recent results of our theoretical studies on Bose gases near resonance or at large scattering lengths. We show that 3D Bose gases near resonance are nearly fermionized, analogous to one-dimensional Tonks-Girardeau gases of hardcore bosons. Furthermore, beyond the Lee-Huang-Yang dilute limit, the chemical potential reaches a maximum when approaching the resonance from the molecule side and an onset instability sets in at a positive critical scattering length. We attribute this peculiar property to the sign change of the effective interactions due to a many-body renormalization effect. The effect of Efimov states on the chemical potential is estimated to be around a few percent.

Reference

[1] D. Borzov, M. Mashayekhi, S. Z. Zhang, J. L. Song and F. Zhou, Phys. Rev. A85, 023620 (2012).

Crystallized merons and inverted merons in the condensation of spin-1 Bose gases with spin-orbit coupling

S.-W. Su[1,*], I.-K. Liu[2], Y.-C. Tsai[3], W. M. Liu[4], and S.-C. Gou[2]

1. Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan,
2. Department of Physics, National Changhua University of Education, Changhua 50058, Taiwan
3. Department of Photonics, Feng Chia University, Taichung 40724, Taiwan
4. Instuite of Physics, Chinese Academy of Sciences , Beijing 100190, P. R. China
**d9522513@oz.nthu.edu.tw*

The non-equilibrium dynamics of a rapidly quenched spin-1 Bose gas with spin-orbit coupling [1] is studied. By solving the stochastic projected Gross-Pitaevskii equation, we show that crystallization of merons can occur in a spinor condensate of 87Rb. The stability of such a crystal structure is analyzed. Likewise, inverted merons can be created in a spin-polarized spinor condensate of 23Na. Our studies provide a chance to explore the fundamental properties of meron-like matter.

Reference

[1] Y.-J. Lin, K. Jimenez-Garcia and I. B. Spielman, *Spin-orbit-coupled Bose-Einstein condensates*, Nature **471**, pp. 83-86 (2011).

Bose-Einstein condensation of ^{85}Rb by direct evaporation in an optical dipole trap

Anna L. Marchant*, Timothy P. Wiles, Manfred M. H. Yu, and Simon L. Cornish

Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK
**a.l.marchant@durham.ac.uk*

Bose-Einstein condensates of ^{85}Rb are produced by direct evaporation in a crossed optical dipole trap [1]. The independent control of the trap frequencies and magnetic bias field afforded by the trapping scheme permits full control of the trapped atomic sample, enabling the collision parameters to be easily manipulated to achieve efficient evaporation in the vicinity of the 155 G Feshbach resonance.

The tunable nature of the atomic interactions in ^{85}Rb makes it possible to initiate a collapse of the condensate which can, in the right trapping geometry, result in the creation of bright matter-wave solitons. These self-stabilizing wave packets arewell localized due to attractive atomic interactions and hence show great potential as surface probes for the study of short-range atom-surface interactions [2]. In light of recent theoretical interest, there is also much scope for the study of binary soliton collisions and the scattering of solitons from barriers with a view to developing interferometry schemes.

References

[1] A. L. Marchant *et al.*, *Bose-Einstein condensation of ^{85}Rb by direct evaporation in an optical dipole trap*, arXiv:1203.6598v1 (2012).
[2] S. L. Cornish *et al.*, *Quantum reflection of bright matter-wave solitons*, Physica D **238**, 1299 (2009).

Cooling by heating a superfluid

D. J. Papoular*, G. Ferrari, L. P. Pitaevskii, and S. Stringari

INO-BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Povo, Italy
**papoular@science.unitn.it*

We consider a uniform superfluid confined in two compartments connected by a superleak and initially held at equal temperatures. If one of the two compartments is heated, a fraction of the superfluid will flow through the superleak. We show that, under certain thermodynamic conditions, the atoms flow from the hotter to the colder compartment, contrary to what happens in the fountain effect observed in superfluid Helium. This flow causes quantum degeneracy to increase in the colder compartment. In superfluid Helium, this novel thermomechanical effect takes place in the phonon regime of very low temperatures. In dilute quantum gases, it occurs at all temperatures below T_c. The increase in quantum degeneracy reachable through the adiabatic displacement of the wall separating the two compartments is also discussed.

Reference

[1] D. J. Papoular, G. Ferrari, L. P. Pitaevskii, S. Stringari, *Increasing Quantum Degeneracy by Heating a Superfluid*, in preparation (2012).

Creating and characterizing vortex clusters in atomic Bose-Einstein condensates

Angela White*, Carlo Barenghi, and Nick Proukakis

School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne, UK
**ang.c.white@gmail.com*

We extend available methods for creating vortices in 2D atomic Bose-Einstein condensates by demonstrating that a moving obstacle, in the form of an elongated paddle, can be used to stir a condensate in two quite different ways, to create clusters of like-signed vortices, or induce vortices that are dispersed. We introduce new statistical measures of clustering based on Ripley's K-function and nearest neighbor techniques which are suitable to the small size and number of vortices in atomic condensates. These measures are applied to analyze the evolution and decay of clustering. The theoretical techniques we present are accessible to experimentalists and extend the current methods of inducing 2D quantum turbulence in Bose-Einstein condensates.

Vortex core deformation in spin-1 BECs

Justin Lovegrove*, Janne Ruostekoski, and Magnus O. Borgh

School of Mathematics, University of Southampton, UK
**j.lovegrove@soton.ac.uk*

We have numerically minimised the free energy of a rotating, spin-1 BEC in 3 dimensions to determine the structure of the core of a singular, singly-quantised vortex. For the polar state, the vortex splits into two half-quantum vortices, each with a ferromagnetic core. In the ferromagnetic state, a hybrid spin disgyration and phase vortex forms, again with the core filled with the polar state. These results agree with studies in 2 dimensions[1, 2], though previously the nature of these core structures has not been understood. We also report on the stability of these vortices for varying spin-dependent scattering lengths, rotation frequencies, linear and quadratic Zeeman splittings in isotropic or strongly oblate harmonic traps.

References

[1] S.-K. Yip, *Internal Vortex Structure of a Trapped Spinor Bose-Einstein Condensate*, Phys. Rev. Lett. 83, 4677 (1999).
[2] T. Mizushima, K. Machida and T. Kita, *Axisymmetric versus nonaxisymmetric vortices in spinor Bose-Einstein condensates*, Phys. Rev. A 66, 053610 (2002).

Stability of ring dark solitons in toroidal Bose-Einstein condensates

Lauri Toikka* and Kalle-Antti Suominen

Department of Physics and Astronomy, University of Turku, 20014 Turku, Finland
**laantoi@utu.fi*

We investigate the effect of toroidal confiment on the stability of ring dark solitons, and propose a simple model to explain the main features of the snake instability [1]. We predict the number of vortex-anti-vortex pairs produced in thesnake instability and compare to numerical simulations. In our simulations toroidal confiment accelerates the onset of the snake instability compared to e.g. a cylindrical trap of similar size.

We also investigate the connection between imaginary Bogoliubov modes and the snake instability using the exact soliton-like dark ring solution of the radial Gross-Pitaevskii equation [2]. There exists only a single imaginary eigenvalue, and we show it corresponds to the snake instability.

References

[1] L. A. Toikka, K-A. Suominen *The Snake Instability of Ring Dark Solitons in Toroidally Trapped Bose-Einstein Condensates*, manuscript in preparation.
[2] L. A. Toikka, J. Hietarinta, K-A. Suominen *Exact Soliton-like Solutions of the Radial Gross-Pitaevskii Equation*, arXiv:1204.3009v1 [cond-mat.quant-gas] (2012).

Tu-056 Bose gases

A hybrid optical and magnetic ultracold atom chip system

Daniel M. Farkas[1,]*, Evan A. Salim[1], Seth Caliga[2], Cameron Straastma[2], and Dana Z. Anderson[1,2]

1. ColdQuanta, Inc., 1600 Range St., Suite 103, Boulder, CO 8030, USA
2. JILA, University of Colorado, and NIST, 440 UCB, Boulder, CO 80309-0440, USA
**daniel.farkas@coldquanta.com*

High resolution optical access (< 1 µm) to ultracold atoms offers new capabilities and insights into applications where single-site resolution and control of optical lattices is warranted [1, 2]. Using ColdQuanta's GlasSi™ atom chips, we have demonstrated high-resolution imaging and optical control in a vacuum system small enough to be held in one's hand. GlasSi atom chips have substrates comprised of arbitrarily defined glass and silicon regions. Using these chips, ^{87}Rb BECs were produced within 100 µm of a window in the atom chip. Using high numerical aperture (NA) optics placed *outside of the vacuum* system and within 1 mm of the atoms, we obtained resolutions of 2.5 µm, which is within a factor of 4 for the NA of 0.6 and imaging wavelength of 780 nm. Using the optics in reverse, optical potentials can be projected onto the atoms with the same high resolutions. As an example, we show images of a BEC sliced into multiple pieces by a blue-detuned laser.

References

[1] W. S. Bakr, A. Peng, M. E. Tai, R. Ma, J. Simon, J. I. Gillen, S. Fölling, L. Pollet and M. Greiner, Science **329**, 547 (2010).
[2] J. F. Sherson, C. Weitenberg, M. Endres, M. Cheneau, I. Bloch and S. Kuhr, Nature **467**, 68 (2010).

Critical rotation of an annular superfluid Bose gas

Romain Dubessy, Thomas Liennard, Paolo Pedri, and Hélène Perrin*

Laboratoire de physique des lasers, CNRS and Université Paris 13, 99 avenue J.-B. Clément, F-93430 Villetaneuse
**helene.perrin@univ-paris13.fr*

After the pioneering work on persistent flow in helium, recent experimental success at producing circulating superfluid flow of Bose gases in annular traps has focused interest on the issue of dissipation of this macroscopic quantum state.

In this work [1], we analyze the excitation spectrum of a superfluid Bose-Einstein condensate rotating in a ring trap. We identify two important branches of the spectrum related to external and internal surface modes that lead to the instability of the superfluid. Depending on the initial circulation of the annular condensate, either the external or the internal modes become first unstable. This instability is crucially related to the superfluid nature of the rotating gas. In particular we point out the existence of a maximal circulation above which the superflow decays spontaneously, which cannot be explained by invoking the average speed of sound.

Reference
[1] R. Dubessy, T. Liennard, P. Pedri, and H. Perrin, *Critical Rotation of an Annular Superfluid Bose Gas*, arXiv:1204.6183 (2012).

High-contrast spatial interference of condensates

Chris Carson, Mateusz E. Zawadzki, Paul F. Griffin, Erling Riis, and Aidan S. Arnold

Dept. of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK

We use magnetic levitation and a variable-separation dual optical plug to obtain clear spatial interference between two condensates axially separated by up to 0.25mm – the largest separation observed with this kind of interferometer. Clear planar fringes are observed using standard (i.e. non-tomographic) resonant absorption imaging. The ‘magnifying’ effect of a weak inverted parabola potential on fringe separation is observed and agrees well with theory [1]. With longer levitation we recently observed single-shot interference contrasts of 95%, close to the theoretical limit due to pixellation of the sinusoidal fringes on our CCD camera.

Reference
[1] M. E. Zawadzki, P. F. Griffin, E. Riis, and A. S. Arnold, *Spatial interference from well-separated split condensates*, Phys. Rev. A **81**, 043608 (2010).

Hanbury Brown and Twiss correlations across the Bose-Einstein condensation threshold

A. Perrin[1,2,3,*], R. Bücker[1], S. Manz[1], T. Betz[1], C. Koller[1],
T. Schumm[1], and J. Schmiedmayer[1]

1. Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria
2. Wolfgang Pauli Institute, 1090 Vienna, Austria
3. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, 99 Avenue J.-B. Clément, 93430 Villetaneuse, France
**aurelien.perrin@univ-paris13.fr*

The seminal experiments of Hanbury Brown and Twiss on the measurement of photon correlations have been pivotal to the advancement of quantum optics. Drawing on the analogy between photons and atoms, similar methods have recently been developed for matter waves sources. Relying on the single atom sensitivity of a novel fluorescence detection scheme, we have measured the density density correlation of Bose gases across the phase transition to Bose-Einstein condensation [1]. We are able to observe the gradual establishment of long range order while still being sensitive to the residual thermal excitations in the system. Moreover, we observe an anticorrelation at finite distances that can already been qualitatively interpreted within ideal gastheory.

Reference

[1] A. Perrin, R. Bücker, S. Manz, T. Betz, C. Koller, T. Plisson, T. Schumm and J. Schmiedmayer, *Hanbury Brown and Twiss correlations across the Bose-Einstein condensation threshold*, Nat. Phys. **8**, pp. 195-198 (2012).

Recurrence time of quantum dynamics in the interacting 1D Bose gas

Eriko Kaminishi[1], Jun Sato[1], Rina Kanamoto[2], and Tetsuo Deguchi[1]

1. Department of Physics, Graduate School of Humanities and Sciences, Ochanomizu University, Tokyo, Japan
2. Department of Physics, Meiji University, Kawasaki, Kanagawa, Japan
**g1170605@edu.cc.ocha.ac.jp*

The quantum dynamics of interacting particles has recently attracted much interest associated with the question of “equilibration” and “thermalization” of isolated systems. In Ref. [1] the exact relaxation dynamics of a localized many-body state in the 1D Bose gas has been shown explicitly through the Bethe-ansatz method. Here, the localized many-body state gives a localized density profile which is the same with that of a dark soliton in the Gross-Pitaevskii equation. In our study, we calculate the dynamics of a quantum soliton exactly and observe the localized state collapsing into a flat profile in equilibrium for a large number of particles. Furthermore, we show a recurrence phenomenon for a small number of particles. In this presentation, we report the result of the dependence of the recurrence time on the number of particles and the interaction strength.

Reference

[1] J. Sato, R. Kanamoto, E. Kaminishi, and T. Deguchi, “Exact Relaxation Dynamics of a Localized Many-Body State in the 1D Bose Gas”, Phys. Rev. Lett. **108**, 1140401 (2012).

Intensity correlations of Bose-Einstein-condensed light in a dye microcavity

J. Klaers*, J. Schmitt, T. Damm, D. Dung, F. Vewinger, and M. Weitz

Institut für Angewandte Physik, Bonn, Germany
**klaers@iap.uni-bonn.de*

In recent work, we have observed Bose-Einstein condensation of a two-dimensional photon gas in an optical microcavity [1]. Here, the transversal motional degrees of freedom of the photons are thermally coupled to the cavity environment by multiple absorption-fluorescence cycles in a dye medium, with the latter serving both as a heat bath and a particle reservoir. Due to particle exchange between photon gas and molecular reservoir, grandcanonical experimental conditions are expected to be realized in this system – unlike in the presently available atomic BEC experiments. Under these conditions, a regime with strong fluctuations of the condensate number (fluctuation catastrophe) is theoretically expected [2]. I will give an update on the current status of our theoretical and experimental work.

References
[1] J. Klaers, J. Schmitt, F. Vewinger, and M. Weitz, *Bose-Einstein condensation of photons in an optical microcavity*, Nature **468**, pp. 545-548 (2010).
[2] J. Klaers, J. Schmitt, T. Damm, F. Vewinger, and M. Weitz, *Statistical Physics of Bose-Einstein-Condensed Light in a Dye Microcavity*, Phys. Rev. Lett. (in press), arXiv1201.0444 (2012).

Bose gases Tu-062

Ab initio stochastic model for 2D Bose gas experiments: no free parameters

Nick P. Proukakis* and Stuart P. Cockburn

Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics,
Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
**nikolaos.proukakis@ncl.ac.uk*

Following the successful description of atom chip experiments [1], the stochastic Gross-Pitaevskii equation (SGPE) is shown to give an excellent *ab initio* description of weakly interacting, finite temperature two-dimensional Bose gases, accurately reproducing the experiment of Hung *et al.* [2]. This is achieved by addressing a common limitation of 'classical field' applications to date, associated with the appropriate momentum cut-off choice in the otherwise divergent 'classical' theory. Using a systematic approach based on the modified Popov theory [3], we show how to fix the momentum cut-off inherent in the SGPE so that it no longer corresponds to a free parameter. The excellent agreement between theory and experiment shown here at equilibrium forms an important basis for future studies of the dynamics of non-equilibrium 2D Bose gases. We acknowledge funding from EPSRC (EP/F055935/1).

References
[1] S. P. Cockburn, D. Gallucci and N. P. Proukakis, *Quantitative study of quasi-one-dimensional Bose gas experiments via the stochastic Gross-Pitaevskii equation*, Phys. Rev. A **84**, 023613 (2011).
[2] C-L. Hung, X. Zhang, N. Gemelke, C. Chin, *Observation of scale invariance and universality in two-dimensional Bose gases*, Nature **470**, pp. 236-239 (2011).
[3] U. Al Khawaja, J. O. Andersen, N. P. Proukakis, and H. T. C. Stoof, *Low dimensional Bose gases*, Phys. Rev. A **66**, 013615 (2002).

Engineering entanglement for metrology with rotating matter waves

L. M. Rico Gutierrez*, T. P. Spiller, and J. A. Dunningham

School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
**pylmrg@leeds.ac.uk*

By rotating a collection of ultracold bosons in an asymmetric trapping potential at just the right frequency, it is possible to induce a quantum phase transition between two macroscopically distinct states. A recent theoretical study [1] has shown that for weakly interacting systems the critical frequency at which this occurs can be predicted accurately by considering only the lowest Landau level (LLL) and that the resulting state is highly entangled. We consider a more detailed calculation and show the surprising result that, although the LLL approximation predicts the frequency well, it is a very poor predictor of both the quantum Fisher information and the precise form of the entangled state. This issues a warning about relying on this approximation for certain applications. Our more detailed calculation reveals a rich system for engineering a range of interesting entangled states with potential applications to quantum metrology.

Reference

[1] D. Dagnino, N. Barberan, M. Lewenstein, and J. Dalibard, Nature Physics **5**, 431 (2009).

Quantum Kinetic Theory of Collisionless Superfluid Internal Convection

Lukas Gilz* and James R. Anglin

Fachbereich Physik, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany
**lgilz@rhrk.uni-kl.de*

Superfluids can transport heat independently of mass via simultaneous opposite flows of their spatially interpenetrating superfluid and thermal components. This phenomenon of internal convection is known from experiments on superfluid Helium and is usually described within Landau's phenomenological two fluid hydrodynamics. Applying quantum kinetic theory to a dilute Bose gas held between two thermal reservoirs at different temperatures, we identify the same phenomena in the collisionless Bogoliubov regime of a Bose-condensed gas [1]. The emergence of internal convection as an environmentally induced coherent effect requires a long quasi-particle lifetime within the thermal reservoirs, and its analysis needs explicit treatment of non-resonant master equation terms. Our results for the energy and particle currents suggest that internal convection should be directly observable in currently feasible experiments on trapped ultracold vapors.

Reference

[1] Lukas Gilz, James R. Anglin, *Quantum Kinetic Theory of Collisionless Superfluid Internal Convection*, Phys. Rev. Lett. **107**, 090601 (2011).

Instabilities of periodic soliton patterns with a long-ranged interaction

Yi-Chan Lee[1,*], YuanYao Lin[2], and Ray-Kuang Lee[1,2]

1. Physics Department, National Tsing-Hua University, Hsinchu 300, Taiwan
2. Institute of Photonics Technologies, National Tsing-Hua University, Hsinchu 300, Taiwan
**xellosslee@gmail.com*

We study the existence and stability of self-organized periodic soliton solutions in the quasi-one-dimensional homogeneous system, but with a long-ranged interaction. The imposed period condition induces oscillatory unstable modes when the degree of long-ranged interaction is small; while the system involves into a quasi-linear and stable one when the long-ranged interaction is large. In terms of Jacobian elliptic functions, parameter space to support stable period soliton patterns would be illustrated.

References

[1] L. D. Carr, C. W. Clark, and W. P. Reinhardt, Phys. Rev. A **62**, 063610 (2000).
[2] Y. Y. Lin, R.-K. Lee, Y.-M. Kao, and T.-F. Jiang, Phys. Rev. A **78**, 023629 (2008).
[3] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau, Rep. Prog. Phys. **72**, 12640 (2009).

Bose gases Tu-066

Towards probing quantum many-body systems with single atom resolution

Dominik Fischer*, W. Rohringer, F. Steiner, M. Trupke, and J. Schmiedmayer

Vienna Center for Quantum Science and Technology, Vienna, Austria
**dfischer@ati.ac.at*

Based on our experience with single-atom detection using integrated micro-optics [1] we build a new experiment heading for a detection efficiency of > 0.95. This will enable us to study properties of single atoms as well as interatomic correlations at shot noise limit. In combination with standard imaging techniques we can compare the macroscopic properties of Bose-Einstein condensates with the coherence properties of its constituents. Using the flexibility of our atom chip in sculpturing different magnetic potentials, we will be able to study different regimes: 3D condensates and quasicondensates both in equilibrium as well as in a controlled 1D expansion, thus entering the regime of non-equilibrium dynamics.

As a second project we are going to combine magnetic chip traps with photonic structures, namely tapered nanofibers and photonic crystal fibers in order to strongly couple light to a tightly confined atomic ensemble, enabling us to study EIT, light storage and polariton gases in a quasi 1D geometry.

Reference

[1] D. Heine, W. Rohringer, D. Fischer, M. Wilzbach, T. Raub, S. Loziczky, X. Liu, S. Groth, B. Hessmo and J. Schmiedmayer, New J. Phys. **12**, 095005 (2010).

A mesoscopic gas of spin 1 bosons

Lingxuan Shao*, David Jacob, Vincent Corre, Jean Dalibard, Fabrice Gerbier, Emmanuel Mimoun, and Luigi de Sarlo

Laboratoire Kastler Brossel, 24 rue Lhomond, 75005 Paris, France
**lingxuan.shao@lkb.ens.fr*

One of the most active topic in the field of ultra cold quantum gases is the study of interacting many-body systems with spin [1,2]. Atoms with arbitrary Zeeman structure can be trapped by far-detuned optical traps. In our group, we construct an all-optical setup in order to study spin 1 condensates in sodium gases. We achieved to reach Bose-Einstein condensation regime by MOT pre-cooling and two-stages evaporative cooling, with about 5000 atoms. We explore the phase diagram with magnetization and magnetic field at low temperature in equilibrium state. Two phases are found, reflecting a competition between the spin-dependent interaction and the quadratic Zeeman energy. The measurements are in quantitative agreement with mean-field theory and single mode approximation. We also notice an abnormal large fluctuation at small magnetization and low magnetic field, which opens future works for us.

References

[1] T.-L. Ho, Phys. Rev. Lett. 81, 742 (1998).
[2] T. Ohmi and T. Machida, J. Phys. Soc. Jpn 67, 1822 (1998).

Nonthermal fixed points and superfluid turbulence in an ultracold Bose gas

Sebastian Erne, Markus Karl, Boris Nowak, Nikolai Philipp, Jan Schole, and Thomas Gasenzer*

1. Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
2. ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany
**t.gasenzer@uni-heidelberg.de*

Turbulence appears in situations where, e.g., an energy flux goes from large to small scales where finally the energy is dissipated. As a result the distribution of occupation numbers of excitations follows a power law with a universal critical exponent. The situation can be described as a nonthermal fixed point of the dynamical equations. Single-particle momentum spectra for a dynamically evolving Bose gas are analysed using semi-classical simulations and quantum-field theoretic methods based on effective-action techniques. These give information about possible universal scaling behaviour. The connection of this scaling with the appearance of topological excitations such as solitons and vortices is discussed. For the one-dimensional case, a random-soliton model provides analytical results for the spectra, and their relation to those found in a field-theory approach to strong wave turbulence is discussed. The results open a view on solitary wave dynamics from the point of view of critical phenomena far from thermal equilibrium and on a possibility to study non-thermal fixed points and superfluid turbulence in experiment without the necessity of detecting solitons and vortices in situ.

Reference

[1] B. Nowak *et al.*, Phys. Rev. B 84, 020506(R) (2011); B. Nowak *et al.*, arXiv:1111.6127 [cond-mat] (2011); J. Schole *et al.*, arXiv:1204.2487 [cond-mat] (2012).

Rapid formation of Rubidium Bose-Einstein Condensates in a crossed dipole trap with tunable trap aspect ratio

Chun-Chia Chen[1,2,*], Chin-Yuan Huang[1], Guan-Bo Liao[1], and Ming-Shien Chang[1]

1. Institute of Atomic and Molecular Sciences, Academia, Taipei, Taiwan
2. Department of Physics, National Taiwan University, Taipei 10617, Taiwan
**chenchunchia@gmail.com*

We report on the rapid formation of Rubidium Bose-Einstein Condensates (BEC) in a dipole trap. The experiment comprises a simple vapor cell MOT and two single-focused Nd:YAG laser beams crossing at a small angle. The two dipole beams, each with 8 W of power, are tightly focused and are overlapped with the MOT. The laser-cooled atoms are directly loaded into the dipole trap and are forced to evaporate till the formation of BEC. Tuning the crossing angle of the two single-focused beams allows us to greatly tune the longitudinal trap frequency, as well as the effective trap volume, which play important roles for the initial loading number and subsequent efficiency of evaporation. We will report the study details and future direction of this experiment.

Reference

[1] Barrett, M. D., Sauer, J. A. & Chapman, M. S. All-optical formation of an atomic Bose-Einstein condensate. Phys. Rev. Lett. **87**, 010404 (2001).

Ultra-sensitive in situ imaging for matter-wave optics

M. Pappa[1,2], P. C. Condylis[1,3], G. O. Konstantinidis[1,2], V. Bolpasi[1,2], A. Lazoudis[1], O. Morizot[1,4], D. Sahagun[1,3], M. Baker[1,5], and W. von Klitzing[1,*]

1. IESL-FORTH, Vassilika Vouton PO Box 1527, GR-71110 Heraklion, Greece
2. Physics Department, University of Crete, GR711 03 Heraklion Crete, Greece
3. Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2 117542 Singapore, Singapore
4. Current address: Université de Provence, Physique des Interactions Ioniques et Moléculaires (UMR 6633), Centre de St Jérôme, Case C21, F-13397 Marseille Cedex 20, France
5. Current address: The University of Queensland, Brisbane St Lucia, QLD 4072, Australia
**darkimaging@bec.gr*

Quantum degenerate Fermi gases and Bose-Einstein condensates give access to a vast new class of quantum states. The resulting multi-particle correlations place extreme demands on the detection schemes. Here we introduce diffractive dark-ground imaging as a novel ultra-sensitive imaging technique [1]. Using moderate detection optics, we image clouds with less than ten atoms with near-atom shot-noise-limited signal-to-noise ratio. This is an improvement of more than one order of magnitude comparedto our standard absorption imaging. We also analyse the mechanical effects of the probe beam onto the atoms. We show that the resulting Doppler shift has to be taken into account even for moderate saturation intensities ($s=0.1$) and exposure times (100 μs).

Reference

[1] Pappa *et al.* New Journal of Physics 13 (2011) 115012.

Two-body anticorrelation in harmonically trapped Bose gases

T. M. Wright[1,*], A. Perrin[2], A. Bray[1], J. Schmiedmayer[3], and K. V. Kheruntsyan[1]

1. The University of Queensland, School of Mathematics and Physics, Brisbane, QLD 4072, Australia
2. Laboratoire de Physique des Lasers, CNRS and Université Paris 13, 93430 Villetaneuse, France
3. Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria
**todw@physics.uq.edu.au*

Density fluctuations in degenerate Bose gases are quantified by the second-order coherence function [1] $g^{(2)}(\mathbf{r},\mathbf{r}')$, which for ideal and weakly interacting gases typically ranges from values $g^{(2)}(\mathbf{r},\mathbf{r})\approx 2$ at zero separation, to a value of 1 at large separations $|\mathbf{r}-\mathbf{r}'|$. Here we show that nonlocal density-density *anticorrelations* $g^{(2)}(\mathbf{r},\mathbf{r}')<1$ can manifest in a harmonically confined ideal Bose gas. In the grand-canonical ensemble, this phenomenon is obscured by the "fluctuation catastrophe" of the ideal Bose gas [2], and a careful canonical-ensemble treatment of the condensate number fluctuations is required to accurately quantify the magnitude of the anticorrelation. We also discuss how interactions in elongated and quasi-one-dimensional interacting Bose gases suppress the density anticorrelations in position space, but amplify the corresponding anticorrelations in momentum space, and compare our theoretical predictions with the results of recent experiments [3].

References

[1] M. Naraschewski and R. J. Glauber, Phys. Rev. A **59**, 4595 (1999).
[2] V. V. Kocharovsky *et al.*, Adv. At. Mol. Opt. Phys. **53**, 291 (2006).
[3] A. Perrin *et al.*, Nat. Phys. **8**, 195 (2012).

Quantised decay of high charge vortices in an annular BEC

Stuart Moulder*, Scott Beattie, Rob Smith, and Zoran Hadzibabic

Cavendish Lab., JJ Thompson Avenue, Cambridge CB3 0HE
**sm794@cam.ac.uk*

We present work on metastability and decay of multiply-charged superflow in a ring-shaped BEC [1]. A holographically generated Laguerre-Gauss(LG) beam is used to both trap and rotate a condensate of Rb^{87} atoms. The atoms are rotated via a two-photon Raman process using the trapping LG beam with a Gaussian beam to impart a well defined amount of angular momentum in quantised units of $\hbar$. Supercurrent corresponding to a giant vortex with topological charge up to q = 15 is phase imprinted optically and detected both interferometrically and kinematically. We observe q = 3 superflow persisting for over a minute and clearly resolve resolve a cascade of quantised steps in the eventual decay of the supercurrent. These stochastic glitches in the superflow, associated with vortex-induced phase slips, correspond to collective jumps of atoms between discrete q values. Current work is focused on supercurrent decay of a co-rotating spinor condensate, where we find the additional degree of freedom introduced by the two components reduces the stability of superflow.

Reference

[1] S. Moulder, *Quantised superflow glithces in an annular Bose-Einstein condensate*, ArXiv preprint (2012), arXiv:1112.0334.

Interaction between cold atoms and carbon nano tubes

B. Jetter[1,*], J. Märkle[1,α], P. Schneeweiss[1,2], M. Gierling[1],
S. Scheel[3], A. Günther[1], J. Fortǵh[1], and T. E. Judd[1]

1. CQ Center for Collective Quantum Phenomena and their Applications in LISA+,
Physiklaisches Institut, Eberhard-Karls-Universität Tübingen,
Auf der Morgenstelle 14, D-72076 Tübingen, Germany
2. Vienna University of Technology, Institute of Atomic and Subatomic Physics,
Stadionallee 2, 1020 Vienna, Austria
3. Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
**jetter@pit.physik.uni-tuebingen.de,*
[α]maerkle@pit.physik.uni-tuebingen.de

We perform a theoretical study of cold atoms interacting with static and vibrating carbon nanotubes. We construct the full finite temperature Casimir-Polder interaction and explore the scattering of atoms on the tube. We find that elastic quantum reflection can typically be ignored for thermal atom clouds but is important if a Bose-Einstein condensate is used. Atom loss from the condensate is shown to be highly non-trivial, but provided atomic interaction effects and quantum pressure are included in the description , our simulations describe experiments [1] well. Finally, we study a vibrating nanotube in a condensate and show that vibration frequencies typical to nanoscaled objects do not significantly reduce the condensate's coherence, but certain low frequency oscillations dramatically heat the cloud.

Reference

[1] M. Gierling, P. Schneeweiss, G. Visanescu, P. Federsel, M. Haffner, D. P. Kern , T. E. Judd, A. Günther, and J. Fortágh, Nat. Nano. **6**, 446 (2011).

Dynamic Kosterlitz-Thouless transition in 2D Bose mixtures of ultra-cold atoms

L. Mathey[1,*], Kenneth J. Günter[2], Jean Dalibard,[2] and A. Polkovnikov[3]

1. Zentrum für Optische Quantentechnologien and Institut für Laserphysik, Universität Hamburg,
22761 Hamburg, Germany
2. Laboratoire Kastler Brossel, CNRS, UPMC, Ecole Normale Supérieure, 24 rue Lhomond,
F-75005 Paris, France
3. Department of Physics, Boston University, 590 Commonwealth Ave., Boston, MA 02215
**lmathey@physnet.uni-hamburg.de*

We propose a realistic experiment to demonstrate a dynamic Kosterlitz-Thouless transition in ultra-cold atomic gases in two dimensions. With a numerical implementation of the Truncated Wigner Approximation we simulate the time evolution of several correlation functions, which can be measured via matter wave interference. We demonstrate that the relaxational dynamics is well-described by a real-time renormalization group approach, and argue that these experiments can guide the development of a theoretical framework for the understanding of critical dynamics.

This poster is based on Ref. [1].

Reference

[1] L. Mathey, Kenneth J. Günter, Jean Dalibard, and A. Polkovnikov, cond-mat/1112.1204.

Calorimetry of a Bose-Einstein condensate

M. D. Hoogerland* and S. Ruddell

University of Auckland, Department of Physics, Private Bag 92019, Auckland, New Zealand
**m.hoogerland@auckland.ac.nz*

We investigate the heat capacity of a Bose-Einstein Condensate (BEC) following the suggestions by Blakie *et al.* [1]. We start with a BEC of ^{87}Rb atoms, close to zero temperature, trapped in the intersection of two focused CO_2 laser beams. The trap is turned off for times in the order of a millisecond, during which it expands ballistically and falls under gravity. The atoms are then recaptured, and the atoms are allowed to reach thermal equilibrium. Subsequently, the temperatureof the atomic ensemble is measured by time-of-flight. We present some new measurements, varying the interaction strength by the trap depth, as well as the energy transferred by the drop time.

Reference

[1] P. B. Blakie, E. Toth and M. J. Davis, *Calorimetry of Bose-Einstein condensates*, J. Phys. B: At. Mol. Opt. Phys. **40**, 3273 (2007).

Quantum and thermal density fluctuations in 1D Bose gases

Julien Armijo[1,2,3,*]

1. Laboratoire Charles Fabry, Institut d'Optique, Palaiseau, France
2. Departamento de Física, Facultad de Ciencias, Universidad de Chile, Santiago, Chile
3. Center for Optics and Photonics (CEFOP), Concepción, Chile
**jarmijo@cefop.udec.cl*

We have carried precise studies of density fluctuations in weakly repulsive 1D Bose gases held in atom chip traps, using hundreds of pictures and carefully analysing the statistics of atom number in the imaging pixels. Previously, fluctuations were used to precisely study the thermodynamics of 1D Bose gases. Fluctuations up to the third moment were measured and the transition from the ideal gas to the quasicondensate regime was mapped out in the temperature-density space [1]. Observing subpoisonian fluctuations marked the entrance into the quantum quasicondensate regime, and the regime of strong interactions was approached [2]. Here, at record low temperatures, using a non-local analysis at variable observation length, we observe a clear discrepancy with a classical field model which unambiguously proves our direct detection of quantum fluctuations, as the thermodynamic limit breaks down [3].

References

[1] J. Armijo, T. Jacqmin, K. V. Kheruntsyan, and I. Bouchoule, Phys. Rev. Lett. **105**, 230402 (2010), Phys. Rev. A , 021605 (2011).
[2] T. Jacqmin, J. Armijo, T. Berrada, K. V. Kheruntsyan and I. Bouchoule, Phys. Rev. Lett. **106**, 230405 (2011).
[3] J. Armijo, Phys. Rev. Lett. **108**, 225306 (2012).

Thermal spin fluctuations in spinor condensates

M. Melé-Messeguer[1,*], B. Juliá-Díaz[2], A. Polls[1], and L. Santos[3]

1. Universitat de Barcelona, Barcelona, Spain
2. ICFO-Institut de Ciències Fotòniques, Castelldefels (Barcelona), Spain
3. Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover, Germany
**marina@ecm.ub.es*

Spinor gases present a rich physics due to the interplay between internal and external degrees of freedom. We study the finite-temperature physics of spinor condensates in two different scenarios. We first consider dynamically stable spin-1 condensates inthe Zeeman m = 0 state, and study the thermal population of m = 1 via spin-changing collisions. Interestingly, these collisions are typically characterized by a very low energy, and as a consequence, for magnetic fields close to the dynamical instability, the spinor populations may be extremely sensitive to temperature. We then analyze dynamically stable Chromium F = 3 condensates in m = 3, where magnetic dipolar interactions introduce spin relaxation, which leads not only to a very temperature-sensitive population of m = 2, but also to a non-trivial angular dependence of the activated m = 2 atoms. The discussed thermal effects may be employed for thermometry at very low temperatures.

References

[1] L. Santos and T. Pfau, *Spin-3 Chromium Bose-Einstein condensates*, Phys. Rev. Lett. **96**, 190404 (2006).
[2] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein and T. Pfau, *The physics of dipolar bosonic quantum gases*, Rep. Prog. Phys. **72**, 126401 (2009).

Confinement-induced collapse of a dipolar Bose-Einstein condensate

J. Billy[1,*], E. Henn[1], S. Müller[1], T. Maier[1], H. Kadau[1], M. Jona-Lasinio[2], L. Santos[2], A. Griesmaier[1], and T. Pfau[1]

1. Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany
2. Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover, Germany
**j.billy@physik.uni-stuttgart.de*

We experimentally investigate the instability and collapse dynamics of a dipolar Bose-Einstein condensate (dBEC) in a 1D optical lattice. In contrast to the usual method relying on a change in the interaction strength, the instability is here initiated by a modification of the external confinement potential, while keeping the interaction strength constant. Only a dBEC offers this possibility, since its stability depends on the lattice depth due to the anisotropic dipole-dipole interaction [1]. We consider a ^{52}Cr BEC with reduced scattering length, initially confined in a trap created by a shallow optical lattice superimposed to a crossed optical dipole trap. We show that its instability can be induced in-trap by decreasing the lattice depth below a critical value. We also show that a dBEC initially stabilized by the lattice may become unstable and collapse during the time-of-flight dynamics upon release, which is a unique feature of dipolar systems in optical lattices.

Reference

[1] S. Müller *et al.*, "Stability of a dipolar Bose-Einstein condensate in a one-dimensional lattice", Phys. Rev. A **84**, 053601 (2011).

Observation of Feshbach resonances in ultracold Er gases

A. Frisch[1], K. Aikawa[1], M. Mark[1], S. Baier[1], M. Springer[1], R. Grimm[1,2], and F. Ferlaino[1]

1. Institut für Experimentalphysik and Zentrum für Quantenphysik,
Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
2. Institut für Quantenoptik und Quanteninformation,
Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria

We report on the first measurements of Feshbach resonances in ultracold gases of submerged-shell atoms. Our experiments focus on ^{168}Er, which is a highly magnetic atom of the lanthanide series. Because of its large magnetic moment of 7 μ_B, with μ_B the Bohr magneton, and a non-*S* electronic ground state, Er features very strong anisotropic interactions, which are not accessible with alkali atoms. It has recently been predicted that Feshbach resonances in lanthanide atoms, as Er and Dy, are induced by the strong anisotropy of the dispersion interaction and magnetic dipole-dipole interaction [1]. Our measurements show a rich Feshbach spectrum in the low magnetic field region below 50 G and thus give first insights into the scattering physics of lanthanide atoms.

Reference

[1] A. Petrov, E. Tiesinga and S. Kotochigova, arXiv:1203.4172, 2012.

Towards stable groundstate NaK molecules

Nikolaus Buchheim, Zhenkai Lu, Nathan Evetts, Ingo Laut, Tobias Schneider,
Christoph Gohle, and Immanuel Bloch

Max-Planck-Institute for Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
**tobias.schneider@mpq.mpg.de*

Ultracold quantum gases can serve as bench mark systems for strongly interacting manybody physics [1]. Conventional alkali atomic systems at ultra low temperatures exhibit interaction potentials that have essentially zero range. If long range interaction can be introduced, many intriguing effects and new quantum phases will be accessible. Examples are real space long range (crystalline) order for bulk systems, supersolids and fractional Mott insulators in optical lattices. Two promising candidates for ultra cold particles with tunable long range interaction are Rydberg atoms and ground state polar molecules. We are setting up an experiment to create ultracold NaK molecules. In this system instability due to inelastic two body collisions known from pioneering experiments [2] is absent and chances are good to reach far into the interesting parameter space.

References

[1] I. Bloch, J. Dalibard and W. Zwerger, *Many-body physics with ultracold gases*, Rev. Mod. Phys. **80**, 885 (2008).
[2] K. K. Ni *et al.*, *A high phase-space-density gas of polar molecules*, Sience, **322**, 231 (2008).

Dipolar gases

Markus Debatin[1,*], Lukas Reichsöllner[1], Tetsu Takekoshi[1,2], Verena Pramhaas[1], Karl Hippler[1], Francesca Ferlaino[1], Rudolf Grimm[1,2], and Hanns-Christoph Nägerl[1]

1. Institut für Experimentalphysik Universität Innsbruck
2. Institut für Quantenoptik und Quanteninformation (IQOQI) Innsbruck
**Markus.debatin@uibk.ac.at*

Dipolar quantum gas systems at ultralow temperatures are expected to exhibit novel many-body quantum phases as a result of the long-range and anisotropic dipole-dipole interaction. The present work focuses on the creation of ultracold samples of polar ground-state RbCs molecules. We first produce two spatially separated Bose-Einstein condensates (BEC) of Rb and Cs atoms [1]. After overlapping the BECs we produce weakly bound RbCs molecules [2] using the Feshbach-association technique. We transfer the molecules into the rovibrational ground state[3] with 90% efficiency by employing the STIRAP (Stimulated Raman Adiabatic Passage) method. Our next goal is to improve the production efficiency for the RbCs molecules by performing the Feshbach association and STIRAP transfer in the presence of an optical lattice.

References

[1] A. Lercher *et al.*, “Production of a dual-species Bose-Einstein condensate of Rb and Cs atoms”, EUR PHYS J D **65**, pp. 3 (2011).
[2] T. Takekoshi *et al.*, “[…] Feshbach resonances, weakly bound states, and the coupled-channel model”, PRA **5**, pp. 032506 (2012).
[3] M. Debatin *et al.*, “Molecular spectroscopy for ground-state transfer of ultracold RbCs molecules”, PCCP **13**, pp. 18926 (2011).

Dipolar gases Tu-082

Evaporative cooling of polar molecules

Brian Neyenhuis*, Bo Yan, Steven A. Moses, Jacob P. Covey, Jun Ye, and Deborah S. Jin

JILA, NIST, and University of Colorado Department of Physics, Boulder, Colorado USA
**brian.neyenhuis@colorado.edu*

Ultracold polar molecules in the quantum degenerate regime open the possibility of realizing strongly correlated quantum systems with long-range and spatially anisotropic interactions. Although KRb is observed to undergo bi-molecular chemical reactions at ultralow temperatures [1], the anisotropy of the dipole-dipole interaction can be exploited to suppress these chemical reactions by trapping the molecules in a one-dimensional optical lattice [2]. In this reduced 2D geometry, the repulsive dipole-dipole interaction further enhances the p-wave barrier between two indistinguishable fermionic molecules, drastically reducing the chemical reaction rate. We now demonstrate evaporative cooling of KRb in this reduced geometry. Although s-wave scattering is forbidden by quantum statistics and the rethermalization rate from p-wave collisions is negligible, the molecules rethermalize via long range dipole-dipole interactions. The observed increase in phase space density is an important step towards the exploration of collective quantum effects in an ultracold gas of molecules.

References

[1] S. Ospelkaus *et al.*, “Quantum-State Controlled Chemical Reactions of Ultracold Potassium-Rubidium Molecules”, Science **327**, pp. 853 (2010).
[2] M. H. G. de Miranda *et al.*, “Controlling the Quantum Stereodynamics of Ultracold Bimolecular Reactions”, Nature Physics **7**, pp. 502 (2011).

Ultracold dipolar Bose-Einstein condenstates in an optical lattice

Sung Mi Yoo[1,*], Young Soon Kim[2], and Sun Mok Paik[3]

1. Department of Electron Physics, Hallym University, 1 Hallymdaehakgil, Chuncheon, Ganwon-do 200-702, Republic of Korea
2. Department of Physics, Myongji University, 116 Myongji-ro, Cheoin-gu, Yongin, Gyeonggi-do 449-728, Republic of Korea
3. Department of Physics, Kangwon National University, Chuncheon, Ganwon-do 200-701, Republic of Korea
**smy@hallym.ac.kr*

Most researches on quantum degenerate gases in optical lattices so far have considered only short-ranged, isotropic, and Van der Waals type interactions of alkali atoms. However, recent experimental realizations [1, 2] of almost pure dipolar gases of dysprosium-161 and erbium-168 offer fascinating opportunities to study how long-ranged, anisotropic, and dipole-dipole interactions modify the properties of trapped quantum gases of bosons and fermions. We have investigated collective excitation of dipolar bosons trapped in a 2D optical lattice using numerical simulations for different trap geometries. It is found that anisotropic trap has great impact on the collective mode shift. As the number of atoms decreases, our result demonstratesdisagreement with the one predicted in the Thomas-Fermi limit.

References

[1] M. Lu, N. Q. Burdick, and B. L. Lev, *Quantum Degenerate Dipolar Fermi Gas*, Phys. Rev. Lett. **108**, 210301 (2012).
[2] K. Aikawa, A. Frisch, M. Mark, S. Baier, A. Rietzler, R. Grimm, and F. Ferlaino, *Bose-Einstein Condensation of Erbium*, Phys. Rev. Lett. **108**, 210401 (2012).

Coherent multi-flavor spin dynamics in a fermionic quantum gas

Jannes Heinze*, Jasper Simon Krauser, Nick Fläschner, Sören Götze, Christoph Becker, and Klaus Sengstock

Institut für Laserphysik, Universität Hamburg, Hamburg, Germany
**jheinze@physnet.uni-hamburg.de*

Multi-component fermion systems give rise to many intriguing physical phenomena, such as baryon formation and SU(N) symmetric magnetism. We report on the realization of a spin-9/2 fermionic quantum gas of ^{40}K atoms in an optical lattice and study its fundamental spin-exchange processes [1]. At low magnetic fields, interactions allow for dynamical exchange of the internal spin, while at high fields the spins are stable. The spin dynamics is initialized by a quench of the magnetic field between these regimes. For isolated atom pairs, long-lived coherent oscillations of the spin populations are observed and a spin resonance as a function of the magnetic field is identified. The results are in very good agreement with numerical calculations including all scattering channels. Allowing for tunneling in one direction, we observe a damping of the coherent oscillations. We attribute this to a melting of the initial band insulator, induced by spin-changing collisions which open additional spin channels.

Reference

[1] J. S. Krauser, *et al.*, “Coherent Multi-Flavor Spin Dynamics in a Fermionic Quantum Gas“, arXiv, 1203.0948v1 (2012).

Feynman diagrams versus Fermi-gas Feynman emulator

K. Van Houcke[1,2,*], F. Werner[1,3], E. Kozik[4,5], N. Prokofev[1], B. Svistunov[1],
M. J. H. Ku[6], A. T. Sommer[6], L. W. Cheuk[6], A. Schirotzek[7], and M. W. Zwierlein[6]

1. Department of Physics, University of Massachusetts, Amherst, MA 01003, USA
2. Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Ghent, Belgium
3. Laboratoire Kastler Brossel, ENS, UPMC, CNRS, 24 rue Lhomond, 75005 Paris, France
4. Theoretische Physik, ETH Zürich, CH-8093 Zürich
5. Centre de Physique Théorique, Ecole Polytechnique, 91128 Palaiseau Cedex, France
6. Department of Physics, MIT-Harvard Center for Ultracold Atoms,
and Research Laboratory of Electronics, MIT, Cambridge, Massachusetts 02139, USA
7. Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
**kris.vanhoucke@ugent.be*

Precise understanding of strongly interacting fermions, from electrons in modern materials to nuclear matter, presents a major goal in modern physics. For the first time, we sum the series of Feynman diagrams for such a many-body problem to essentially infinite order. This is made possible by a new theoretical approach, Bold Diagrammatic Monte Carlo (BDMC), combining a Monte Carlo process capable of sampling billions of diagrams, bold lines representing fully dressed propagators, and divergent-series resummation techniques. Specifically, we compute the equation of state of the unitary gas in the normal unpolarised phase. We cross-validate the results with new precision experiments on ultra-cold ^{6}Li atoms at the broad Feshbach resonance. Excellent agreement demonstrates that a series of Feynman diagrams can be controllably resummed in a non-perturbative regime using BDMC. This opens the door to the solution of challenging problems across many areas of physics.

Fermi gases Tu-086

Topological superfluid in a trapped two-dimensional polarized Fermi gas with spin-orbit coupling

Jing Zhou[1], Wei Zhang[2,*], and Wei Yi[1,†]

1. Key Laboratory of Quantum Information, USTC, CAS, Hefei, Anhui 230026, China P. R.
2. Department of Physics, Renmin University of China, Beijing 100872, China P. R.
**wzhangl@ruc.edu.cn; † wyiz@ustc.edu.cn*

We study the stability region of the topological superfluid phase in a trapped two-dimensional polarized Fermi gas with spin-orbit coupling and across a BCS-BEC crossover. Due to the competition between polarization, pairing interaction, and spin-orbit coupling, the Fermi gas typically phase-separates in the trap. Employing a mean-field approach that guarantees the ground-state solution, we systematically study the structure of the phase separation and investigate in detail the optimal parameter region for the preparation of the topologically nontrivial superfluid phase. We then calculate the momentum space density distribution of the topological superfluid state and demonstrate that the existence of the phase leaves a unique signature in the trap integrated momentum space density distribution which can survive the time-of-flight imaging process [1].

Reference

[1] J. Zhou, W. Zhang and Y. Wei, Phys. Rev. A **84**, 063603 (2011).

Dynamic spin response of a strongly interacting Fermi gas

Sascha Hoinka[1], Marcus Lingham[1], Marion Delehaye[1,2], and Chris J. Vale[1,*]

1. Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne 3122, Australia
2. Departement de Physique, Ecole Normale Superieure, 24 rue Lhomond, 75005 Paris, France
**cvale@swin.edu.au*

Two-component Fermi gases near Feshbach resonances exhibit universal properties and provide a well controlled setting to explore many-body phenomena in highly correlated quantum systems. Probing dynamic response functions, such as the dynamic spin susceptibility, can reveal new universal aspects in the dynamics of these systems. Here we present the first measurement of the dynamic spin response of a strongly interacting ^{6}Li Fermi gas in the two ground states using Bragg spectroscopy. By appropriate choice of the Bragg laser detuning either the spin or the density response can be measured independently. This allows full characterisation of the spin-parallel and spin-antiparallel components of the dynamic $S(k, \omega)$ and static $S(k)$ structure factors. At high momentum transfer k, the spin response is suppressed at low energies due to pairing and displays a universal high frequency tail, decaying as $\omega^{-5/2}$, where $\hbar\omega$ is the probe energy [1,2].

References
[1] H. Hu and Xia-Ji Liu, *Universal dynamic structure factor of a strongly correlated Fermi gas*, Phys. Ref. A **85**, 023612 (2012).
[2] S. Hoinka *et al.*, *Dynamic spin response of a strongly interacting Fermi gas*, arXiv:1203.4657 [cond-mat.quant-gas] (2012).

Low temperature properties of the fermionic mixtures with mass imbalance in optical lattice

Nayuta Takemori* and Akihisa Koga

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
**takemori@stat.phys.titech.ac.jp*

Mass imbalanced system has attracted current interest since the successful realization of the superfluid (SF) state in the Fermi-Fermi mixtures with distinct ions, ^{40}K and ^{6}Li [1,2]. One of the interesting problems in such a mass imbalanced system is how the SF state is realized in the optical lattice. It is known that in the lattice model, a density wave (DW) state is stabilized since less mobile fermions tend to crystallize. Therefore, it is necessary to clarify how the SF state coexists or competes with the DW state at low temperatures. Here, we studyf the infinite-dimensional attractive Hubbard model with different masses [3], combining dynamical mean-field theory with the continuous time quantum Monte Carlo simulations. It is clarified that the coexisting (supersolid) state is indeed realized in the mass imbalanced system [4]. The low-temperature phase diagram is then determined.

References
[1] M. Taglieber, *et al.*, Phys. Rev. Lett. **100**, 010401 (2008).
[2] E. Wille, *et al.*, Phys. Rev. Lett. **100**, 053201 (2008).
[3] T. Dao, A. Georges, and M. Capone, Phys. Rev. B **76**, 104517 (2007).
[4] N. Takemori and A. Koga, arXiv:1204.1783.

Conduction properties of ultracold fermions

Jakob Meineke*, David Stadler, Sebastian Krinner, Jean-Philippe Brantut, and Tilman Esslinger

Institute for Quantum Electronics, ETH Zurich, Switzerland
**meineke@phys.ethz.ch*

We experimentally study the conduction properties of ultracold fermionic atoms flowing through a quasi two-dimensional channel connecting macroscopic, incoherent reservoirs. An atomic current is induced by creating an imbalance in the particle number of the two reservoirs. Combining the measurement of the current with the high-resolution in-situ measurement of the density in the channel, we observe the drop of chemical potential due to the contact resistance which develops at the contacts between the ballistic channel and the reservoirs [1].

Analogous to a field-effect transistor, we use an additional beam to independently tune the atomic density in the channel region and study the current as a function of the chemical potential. For a strongly interacting Fermi gas we observe a striking increase of the current which we attribute to the onset of superfluidity. We also study the effect of disorder for weakly and strongly interacting Fermi gases.

Reference

[1] J. Brantut, J. Meineke, D. Stadler, S. Krinner, and T. Esslinger. *Conduction of Ultracold Fermions Through a Mesoscopic Channel*. arXiv:1203.1927 (2012).

Attractive and repulsive Fermi polarons in two dimensions

M. Koschorreck*, D. Pertot, E. Vogt, B. Fröhlich, M. Feld, and M. Köhl

Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, UK
**mk673@cam.ac.uk*

The dynamics of a single impurity in an environment is a fundamental question in many-body physics. A spin-up impurity dressed by a bath of spin-down particles, constitutes the Fermi polaron problem. This is the extreme, but conceptually simple, limit oftwo important quantum many-body problems: the BEC-BCS crossover with spin-imbalance for attractive interactions and Stoners itinerant ferromagnetism for repulsive interactions. We create and investigate Fermi polarons in two dimensions and measure their spectral function using momentum-resolved photoemission spectroscopy [1]. For attractive interactions we find evidence for the disputed pairing transition between polarons and tightly bound dimers, which provides insight into the elementary pairing mechanism of imbalanced, strongly-coupled two-dimensional Fermi gases. Additionally, for repulsive interactions we study novel quasiparticles, repulsive polarons, whose lifetime determine the possibility of stabilizing repulsively interacting Fermi systems [2].

References

[1] M. Feld, B. Fröhlich, E. Vogt, M. Koschorreck & M. Köhl, Nature **480**, 75-78 (2011).
[2] M. Koschorreck, D. Pertot, E. Vogt, B. Fröhlich, M. Feld & M. Köhl, submitted to Nature.

Possibility of gapless superfluid states of Fermi atoms in triangular optical lattices

Tomonori Fukase[1], Shunji Tsuchiya[1], Daisuke Yamamoto[2], and Tetsuro Nikuni[1]

1. Department of Physics, Faculty of Science, Tokyo University of Science, Tokyo 162-8601, Japan
2. Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan

Fermi superfluids in optical lattices have attracted much attention due to the possibility of simulating superconducting systems with strong correlations. Recently, triangular optical lattices have been realized in order to simulate geometrically frustrated systems [1]. In this poster, we study Fermi superfluids in triangular lattices to investigate the effects of frustration on the superfluid states. Using the attractive Hubbard model, we calculate the superfluid order parameter in the presence of superflow within the BCS-Leggett mean-field theory. We find that finite order parameter solution exists even when the negative energy Bogoliubov quasiparticle states are occupied. This indicates the possibility of gapless superfluid state in contrast to the square lattice case [2]. We discuss the stability of the gapless superfluid states. We calculate the energy spectrum of superfluid collective modes to map out the stability phase diagram.

References

[1] C. Becker *et al.*, ”Ultracold quantum gases in triangular optical lattices”, New J. Phys. **10**, 045014 (2010).
[2] R. Ganesh *et al.*, ”Collective modes and superflow instabilities of strongly correlated Fermi superfluids”, Phys. Rev. A **74**, 031604(2009).

Virial expansion with Feynman diagrams

Xavier Leyronas

Laboratoire de Physique Statistique, Ecole normale supérieure, UPMC Univ Paris 06,
Université Paris Diderot, CNRS, 24 rue Lhomond, 75005 Paris, France
leyronas@lps.ens.fr

Experiments performed on ultracold ^{6}Li atoms have measured the equation of state with great accuraccy [1]. From the high temperature behavior, virial coefficients b_3 and b_4 have been extracted. In this work, we have calculated, using diagramatic techniques, the third virial coefficient b_3 in the whole BEC-BCS crossover. Our approach is analytic, and we get closed expressions for b_3 in terms of the $3-$body T-matrix. We recover in this way the experimental result of Ref.[1] in the unitary limit. Our results for b_3 are also in excellent agreement in the whole BEC-BCS crossover with a previous theoretical work [3] using a totally different approach.

References

[1] S. Nascimbène, N. Navon, K. J. Jiang, F. Chevy, and C. Salomon, Nature **463**, 1057 (2010).
[2] X. Leyronas, Phys. Rev. A **84**, 053633 (2011).
[3] X.-J. Liu, H. Hu, and P. D. Drummond, Phys. Rev. Lett. **102**, 160401 (2009).

Spin-depairing transition in one-dimensional two-component Fermi gases

Shun Uchino[1,*] and Norio Kawakami[2]

1. DPMC-MaNEP, University of Geneva, 24 Quai Ernest-Ansermet, 1211 Geneva, Switzerland
2. Department of Physics, Kyoto University, Kyoto 606-8502, Japan
**Shun.Uchino@unige.ch*

We investigate one-dimensional two-component Fermi gases with a time-dependent gauge field on the spin sector. It is known that the ground state of two-component attractive Fermi gases is filled with bound states of up-spin and down-spin particles and the spin excitation has a gap, which is attributed to the appearance of fermionic superfluidity. By combining the methods of the Bethe ansatz with complex twists and Landau-Dykhne, we show that a spin-depairing transition occurs, which may represent a nonequilibrium transition from fermionic superfluids to normal states with spin currents. We analyze cases of Fermi-Hubbard and Yang-Gaudin models, and show how filling (density) affects the transition probability.

Reference

[1] S. Uchino and N. Kawakami, Phys. Rev. A **85**, 013610 (2012).

General properties of universal Fermi gases in arbitrary dimensions

Manuel Valiente

SUPA, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK
mvalien@phys.au.dk

We consider spin-1/2 Fermi gases in arbitrary, integer or non-integer spatial dimensions, interacting via a Dirac delta potential. We first generalize the method of Tan's distributions that implement short-range boundary conditions to arbitrary dimension and then use it to obtain a set of universal relations for the Fermi gas, which serve as dimensional interpolation/extrapolation formulae in between integer dimensions. Using these universal properties we are then able to show that, under very general conditions, effective reduced-dimensional scattering lengths due to transversal confinement depend on the original three-dimensional scattering length in a universal way. As a direct consequence, we find that confinement-induced resonances occur in all dimensions different than two without any need to solve the associated multichannel scattering problem. Finally, we show that reduced-dimensional contacts — related to the tails of the momentum distributions — are related to the actual three-dimensional contact through a correction factor of purely geometric origin.

Strongly interacting mixtures of bosonic ^{23}Na and fermionic ^{40}K

Sebastian Will*, Cheng-Hsun Wu, Jee Woo Park, and Martin W. Zwierlein

MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
**sewill@mit.edu*

Mixtures of bosonic and fermionic quantum gases can form ideal model systems to study intriguing quantum phenomena. Polaron and molecule physics as well as exotic many-body quantum phases become accessible when appropriate Feshbach resonances are available to freely tune the interactions between bosons and fermions. We have created a new quantum degenerate Bose-Fermi mixture of bosonic ^{23}Na and fermionic ^{40}K. We demonstrated that this mixture offers widely tunable interactions via broad interspecies Feshbach resonances [1]. Over thirty resonances were identified, the broadest of which being located at about 138 G and being 30 G wide. Radiofrequency spectroscopy in the vicinity of that resonance has allowed us to create ultracold fermionic Feshbach molecules with lifetimes of up to100 ms. Our work opens up the prospect to create chemically stable, fermionic ground state molecules of ^{23}Na-^{40}K. Due to a large permanent electric dipole moment of 2.72 Debye long-range dipolar interactions will be strong and set the dominant energy scale in many-body systems of fermionic ^{23}Na-^{40}K ground state molecules.

Reference

[1] J. W. Park *et al.*, *Quantum degenerate Bose-Fermi mixture of chemically different atomic species with widely tunable interactions*, Phys. Rev. A **85**, 051602(R) (2012).

Tu-096 Optical lattices

Unconventional superfluidity in higher bands of an optical lattice

Thorge Kock, Arne Ewerbeck, Matthias Ölschläger, Georg Wirth, and Andreas Hemmerich

Institut für Laserphysik, Universität Hamburg, Hamburg, Germany

Atoms trapped in optical lattices have been used successfully to study many-body phenomena. However, the shape that bosonic ground-state wavefunctions can take is limited, apparently compromising the usefulness of this approach. Such limitations, however,do not apply to excited states of bosons. The study of atomic superfluids realized in higher Bloch bands, where orbital degrees of freedom are essential, can bring the world of optical lattices closer to relevant condensed matter systems. We discuss our observations of extremely long coherence times, chiral superfluid order and topological features in higher bands in a square optical lattice.

References

[1] G. Wirth *et al.*, *Evidence for orbital superfluidity in the P-band of a bipartite optical square lattice*, Nature Physics **7** , pp. 147–153 (2011).
[2] M. Ölschläger *et al.*, *Unconventional Superfluid Order in the F Band of a Bipartite Optical Square Lattice*, Phys. Rev. Lett. **106** , 015302 (2011).
[3] M. Ölschläger *et al.*, *Topologically Induced Avoided Band Crossing in an Optical Checkerboard Lattice*, Phys. Rev. Lett. **108**, 075302 (2012).

Matter wave scattering on a time-dependent optical lattice

P. Cheiney*, C. M. Fabre, F. Vermersch, G. L. Gattobigio, R. Mathevet,
T. Lahaye, and D. Guéry-Odelin

Laboratoire de Collisions Agrégats Réactivité, CNRS UMR 5589, IRSAMC,
Université de Toulouse (UPS), 118 Route de Narbonne, 31062 Toulouse CEDEX 4, France
**cheiney@irsamc.ups-tlse.fr*

We experimentally study the scattering of guided matter waves on a time-dependent amplitude optical lattice. We observe different types of frequency-dependent dips in the asymptotic output density distribution. Their positions are compared quantitativelywith numerical simulations. A semiclassical model that combines *local* Floquet-Bloch bands analysis and Landau-Zener transition provides a simple picture of the observed phenomena in terms of elementary absorption-emission Floquet photon processes and Bragg reflections. Finally, we propose and demonstrate the use of this technique with a bichromatic amplitude modulation to design a tunable sub-recoil velocity filter.

Reference

[1] C. M. Fabre, P. Cheiney, G. L. Gattobigio, F. Vermersch, S. Faure, R. Mathevet, T. Lahaye, and D. Guéry-Odelin, Phys. Rev. Lett. **107**, 230401 (2011).

Optical lattices Tu-098

Magnetic lattices for ultracold atoms

Smitha Jose[1], Prince Surendran[1], Leszek Krzemien[1], Shannon Whitlock[2], Mandip Singh[3], Andrei Sidorov[1],
Russell McLean[1], and Peter Hannaford[1,*]

1. Swinburne University of Technology, Melbourne, Australia 3122
2. Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany
3. Indian Institute of Science Education and Research, Mohali, Punjab, India
**phannaford@swin.edu.au*

Magnetic lattices based on periodic arrays of permanent magnetic microstructures [1] provide a promising complementary tool to optical lattices and have certain distinguishing features including the potential to tailor geometries of arbitrary shape, to perform in-situ RF evaporative cooling and RF spectroscopy, and to produce highly stable potentials. Here, we report on the trapping and cooling of ^{87}Rb F=1 atoms in a 1D 10 μm-period magnetic lattice. Typically 3×10^5 atoms are loaded into the magnetic lattice with trap lifetimes of ~ 10 s and evaporatively cooled to 1-2 mK, which is close to the BEC transition temperature. Using *in situ* absorption imaging the clouds of ultracold atoms can be optically resolved in the individual magnetic lattice sites. Potential applications of micron-period magnetic lattices with honeycomb or triangular lattices to simulate condensed matter systems will be presented.

Reference

[1] A. Sidorov and P. Hannaford, “From magnetic mirrors to atom chips”, In *Atom Chips*, Eds. J. Reichel and V. Vuletic, Wiley-VCH Verlag, Weinheim, Ch 1, pp 3-31 (2011).

Dual Mott insulator in a spin-dependent optical lattice

Hirokazu Miyake[1,*], Georgios A. Siviloglou[1], Colin Kennedy[1], David M. Weld[2], and Wolfgang Ketterle[1]

1. MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA
2. Department of Physics, University of California, Santa Barbara, CA, USA
**hmiyake@mit.edu*

A major goal of the field of ultracold atoms is to realize novel many-body states, and in particular magnetic states. It has been suggested that a spin-dependent optical lattice can provide the tunability necessary to realize the Heisenberg Hamiltonian which can give rise to ferromagnetic and antiferromagnetic states [1]. Such a spin-dependent optical lattice can be realized by tuning the laser wavelength close to the D1 and D2 lines of the alkali atoms [2]. We have implemented such a lattice to realize the ability to control the interspin interaction energy for a mixture of two hyperfine states of bosonic ^{87}Rb in a three-dimensional optical lattice. In particular, we have studied the system in a dual Mott insulator state where the two hyperfine states are both Mott insulators and tuned the interspin interaction energy with the spin-dependent optical lattice.

References

[1] L.-M. Duan, E. Demler and M. D. Lukin, *Controlling Spin Exchange Interactions of Ultracold Atoms in Optical Lattices*, Phys. Rev. Lett. **91**, 090402 (2003).

[2] O. Mandel, M. Greiner, A. Widera, T. Rom, T. W. Hänsch and I. Bloch, *Coherent Transport of Neutral Atoms in Spin-Dependent Optical Lattice Potentials*, Phys. Rev. Lett. **91**, 010407 (2003).

Tu-100 Optical lattices

Interplay between interaction and localization in 1D quasiperiodic systems

M. Larcher[1], F. Dalfovo[1,*], M. Modugno[2,3], J. D. Bodyfelt[4], T. V. Laptyeva[4], and S. Flach[4]

1. INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Italy
2. IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain
3. Universidad del Pais Vasco, Bilbao, Spain
4. Max Planck Institute for the Physics of Complex Systems, Dresden, Germany
**dalfovo@science.unitn.it*

Stimulated by recent experiments with ultracold in bichromatic lattices [1], we investigate the evolution of initially localized wave packets in two quasiperiodic models, namely a discrete nonlinear Schrödinger equation and a quartic Klein Gordon lattice. In the regime where, in the absence of nonlinearity, all eigenstates are exponentially localized, we show that the inclusion of a nonlinear term induces a destruction of localization resulting in a subdiffusive spreading. We interpret this delocalization on the basis of mode-mode resonances. Two spreading regimes of weak and strong chaos can be identified by comparing the strength of the nonlinearity with the energy scales of the underlying linear system. For large enough nonlinearity, a wave packet undergoes self-trapping, as in purely random systems. In the quasiperiodic case, however, we find that a partial self-trapping of the expanding wave packet can also occur at weaker nonlinearity due to the existence mini-gaps in the spectrum.

Reference

[1] E. Lucioni, B. Deissler, L. Tanzi, G. Roati, M. Zaccanti, M. Modugno, M. Larcher, F. Dalfovo, M. Inguscio, and G. Modugno, Phys. Rev. Lett. **106**, 230403 (2011).

Engineering Dirac points with ultracold fermions in a tunable optical lattice

Daniel Greif[1,*], Leticia Tarruell[1,2], Thomas Uehlinger[1], Gregor Jotzu[1], and Tilman Esslinger[1]

1. Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland
2. LP2N, Université Bordeaux 1, IOGS, CNRS, 351 cours de la Libération, 33405 Talence, France
**greif@phys.ethz.ch*

We report on the creation of Dirac points with adjustable properties in a tunable honeycomb optical lattice. Using momentum-resolved interband transitions, we observe a minimum band gap inside the Brillouin zone at the position of the Dirac points. We exploit the unique tunability of our lattice potential to adjust the effective mass of the Dirac fermions by breaking the inversion symmetry of the lattice. Changing the lattice anisotropy allows us to move the position of the Dirac points inside the Brillouin zone. When increasing the anisotropy beyond a critical limit, the two Dirac points merge and annihilate each other. We map out this topological transition and find excellent agreement with ab initio calculations. Our results not only pave the way for using cold atoms to model materials where the topology of the band structure plays a crucial role, but also provide the possibility to explore many-body phases resulting from the interplay of complex lattice geometries with interactions.

Optical lattices Tu-102

Rydberg atoms in optical lattices

Sarah E. Anderson* and Georg Raithel

Department of Physics, University of Michigan, Ann Arbor, MI, USA
**andsare@umich.edu*

We investigate highly excited Rydberg atoms in optical-lattice traps. The potential experienced by a Rydberg atom in an optical lattice is given by the spatial average of the free-electron ponderomotive energy due to the laser field, weighted by the Rydberg electron's probability distribution. Here, we study the dependence of the potential on the angular portion of the atomic wavefunction. Experimentally, the angular dependence of the potential is demonstrated using various (j, m_j) levels of ^{85}Rb Rydberg nD states ($50 \leq n \leq 65$) in both an optical lattice (wavelength 1064 nm) and transverse electric field. We present measurements of the lattice depths for various (j, m_j) levels and compare them to theoretical results. The tunability of Rydberg-atom trapping potentials using the angular degrees of freedom will be important for applications of Rydberg-atom optical lattices.

Numerical investigation of electromagnetically induced grating for tripod scheme

M. Gordeev[1,*], E. Efremova[1], and Yu. Rozhdestvensky[2]

1. St.-Petersburg State University, Physics Department, St.-Petersburg, Russia
2. St.-Petersburg State University ITMO, St.-Petersburg, Russia
**mxmgordeev@gmail.com*

The tripod scheme implies that the coupling and probe resonant beams are applied in a two-dimensional geometry [4]. This geometry is particularly appealing as it allows us to study the effect of the phase difference between two standing waves on the diffraction pattern. In this contribution we study the electromagnetically induced phase and amplitude gratings in the tripod configuration scheme. The medium is optically thick and assumed to be homogeneously-broadened. We analyze the four-level scheme driven by the three fields using a density matrix formalism. Thus, our model is based on solving Liouville equations self-consistently with Maxwell equations. Wave equations for the fields are written in the approximation of slowly varying phases and amplitudes. We demonstrate how one can totally suppress diffraction in a desirable diffraction order, or oppositely, amplify a given diffraction order. As for the efficiency of the diffraction in the first diffraction order, it depends on the level of phase modulation, as expected.

References

[1] H. Y. Ling, Y. Q. Li and M. Xiao// Phys. Rev. A **57**, 1338-1344 (1998).
[2] M. Mitsunaga and N. Imoto// Phys. Rev. A **59**, 4773-4776 (1999).
[3] E. Paspalakis and P. L. Knight // J. Opt. B: Quantum Semiclass. Opt, **4**, S372-S375, (2002).
[4] V. Ivanov and Yu. Rozhdestvensky// Phys. Rev. A **81**, 033809 (1998).

Bose-fermi mixtures in one-dimensional incommensurate lattices

Akiko Masaki[1] and Hiroyuki Mori[2]

1. Institute for Solid State Physics,Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8581, Japan
2. Tokyo Metropolitan University, Minamiohsawa 1-1, Hachiohji, Tokyo 192-0397, Japan

Disordered Bose systems with strong correlation, described by Bose Hubbard models with disorder, have been one of the targets of theoretical and experimental investigation. Current interest is also directed towards disordered systems of ultracold atoms generated by using laser speckle patterns or additional incommensurate optical lattice potentials. Fallani *et al.* [1] observed a localization transition of strongly interacting ^{87}Rb bosons in incommensurate lattices, which suggested the formation of a Bose glass.

We numerically studied the localization property of Bose-Fermi mixture systems on one-dimensional incommensurate optical lattices and parabolic confining potentials. We focus on the interaction region where bosons and fermions are in different phases, especially when fermions are localized and bosons are delocalized. Using quantum monte carlo simulation we found new localized or delocalized phases which are formed by bose-fermi interactions and are dependent of the ratio of the density of bosons to that of fermions. We propose a mechanism of these phenomena, showing the visibility of momentum space, the density distributions and the tructure factors.

Reference

[1] L. Fallani *et al.*, Phys. Rev. Lett. **98**, 130404 (2007).

Transport and excitations in lattice-trapped bosonic mixtures

Bryce Gadway[1], Daniel Pertot[1,2], Jeremy Reeves[1], and Dominik Schneble[1,*]

1. Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
2. present address: Cavendish Laboratory, University of Cambridge, Cambridge, UK
**dominik.schneble@stonybrook.edu*

Atomic quantum gases in optical lattices allow for fundamental studies of strongly-correlated many-body systems. We have recently studied transport and excitation effects in 1D atomic mixtures (derived from a BEC) in component-specific lattices. One experiment [1] addressed the effects of uncorrelated disorder, formed by localized impurities, on a lattice-modulated 1D Bose gas. Near the superfluid-to-insulator transition, we observed a shift of the critical lattice depth for the breakdown of transport, in contrast to the case of quasi-disorder from an incommensurate optical lattice, where no such shift is seen. In a second experiment [2] we explored the scattering of atomic de Broglie waves to detect spatial structure in a lattice-modulated 1D Bose gas, as well as the suppression of inelastic scattering in the band structure. Matter-wave Bragg diffraction is a powerful technique to non-destructively probe long-range order, such as in spin mixtures, and its tunability precludes limitations on spatial resolution.

References
[1] B. Gadway, *et al.*, *Glassy Behavior in a Binary Atomic Mixture*, PRL **107**, 145306 (2011).
[2] B. Gadway, *et al.*, *Probing an Ultracold-Atom Crystal with Matter Waves*, arXiv:1104.2564v2 (2/20/2012).

Optical lattices Tu-106

Schwinger-Keldysh approach to a quantum quench in the Bose Hubbard model

Malcolm P. Kennett[1,*] and Denis Dalidovich[2]

1. Physics Department, Simon Fraser University, Burnaby, British Columbia, Canada
2. Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
**malcolmk@sfu.ca*

We use the Schwinger-Keldysh technique to study the real-time dynamics of the Bose-Hubbard model, allowing for a finite-temperature initial state. We find the real-time strong coupling action for the problem at both zero and finite temperature. This action allows for the description of both the superfluid and Mott-insulating phases. We use this action to obtain dynamical equations for the superfluid order parameter as hopping is tuned in real time so that the system crosses the superfluid phase boundary. We find that under a quench in the hopping, the system generically enters a metastable state in which the superfluid order parameter has an oscillatory time dependence with a finite magnitude, but with vanishes under time-averaging. We relate our results to recent out of equilibrium experiments involving cold atoms in traps and point out that equilibration is impeded when the average number of atoms per site differs in the superfluid and Mott insulating phases.

Reference
[1] M. P. Kennett and D. Dalidovich, *Schwinger-Keldysh approach to out-of-equilibrium dynamics of the Bose-Hubbard model with time-varying hopping*, Phys. Rev. A **84**, 033620 (2011).

Resolution assessment of a fluorescence microscope for observing single ytterbium atoms trapped in two-dimensional optical lattice

Yuki Okuyama[1,*], Martin Miranda[1], Akimasa Nakamoto[1], Hitomi Ono[1,†], Masahito Ueda[2], and Mikio Kozuma[1]

1. Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo, Japan
2. Tokyo University, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
**okuyama.y.ab@m.titech.ac.jp*
† Present affiliation: Tokyo University

^{171}Yb atom behaves as an ideal qubit, since its 1/2 nuclear spin has long coherence time. Complicated tasks of quantum information processing will be thus implemented with a 2D quantum gas microscope [1] using the ^{171}Yb atoms. Using a solid immersion lens (SIL), both the resolution and the magnification can be improved by factor of n which is the refractive index of the SIL. The brightness of the microscope can also be improved by factor of n^2. Here we constructed a high-resolution microscope consisting of both a glass-corrected objective lens (N.A.=0.42) and the SIL, and evaluated its resolution using a fluorescence particle with its diameter of 200nm. Obtained resolution was 680nm at 590nm which is center of transmission wavelength of the optical filter (we are planning to detect 556nm of fluorescence from Yb atoms). The chromatic aberration was within 5μm between 399nm and 556nm. Note that we make a deep potential using 399nm laser light at the stage of the fluorescence detection.

Reference
[1] W. S. Bakr, J. I. Gillen, A. Peng, S. Fölling and M. Greiner, *A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice*, Nature **462**, pp. 74-78 (2009).

High-resolution optical spectra of bosonic ytterbium atoms in an optical lattice: comparison between numerical calculations and experiments

K. Inaba[1,3,*], M. Yamashita[1,3], S. Kato[2], K. Shibata[2], R. Yamamoto[2], and Y. Takahashi[2,3]

1. NTT Basic Research labs., NTT Corporation, Atsugi, Kanagawa 243-0198, Japan
2. Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
3. JST, CREST, Chiyoda-ku, Tokyo 102-0075, Japan
**inaba.kensuke@lab.ntt.co.jp*

We investigate laser spectra of bosonic ^{174}Yb atoms in a three dimensional optical lattice both theoretically and experimentally. With the aid of a ultra-narrow optical transition of the Yb atoms [1], high-resolution spectra are systematically measured by varying the lattice depth. We also perform the following numerical simulations; first, determine parameters of the bosonic Hubbard model with the *ab initio* manner; then, analyze this model based on the Gutzwiller approximation considering finite temperature effects; finally, calculate the excitation spectra described by the Lehman representation. Here we consider modifications of the model parameters due to the formation of two-body bound states induced by confinement of the lattice potential [2]. The numerical simulations clarify how the spectra change depending on both temperatures and lattice depths. By comparing the numerical results with the measured spectra, we discuss phase transitions of the present system at finite temperatures.

References
[1] S. Kato, *et al.*, accepted in Appl. Phys. B: Lasers and Optics (2012).
[2] H. P. Büchler, Phys. Rev. Lett. **104**, pp. 090402 (2010).

Single-particle excitation spectrum and correlation effects in a Bose-Fermi mixture

Kazuto Noda*, Robert Peters, and Norio Kawakami

Kyoto University, Kitashirakawa, Sakyo, Kyoto 606-8502, Japan
**noda@scphys.kyoto-u.ac.jp*

Realizations of the Bose-Fermi Hubbard model in an optical lattice have been demonstrated by S. Sugawa, *et al.* [1]. Encouraged by these experiments, we have investigated correlation effects in a mixture of interacting bosons and polarized fermions [2]. We show that novel correlation effects inherent in the mixture system appear in the presence of the boson superfluidity. We demonstrate that the correlation effects form a peak structure in the single-particle excitation spectrum for the fermions in metal, insulator, and supersolid phases. We also address how the effects appear in a mixture of bosons and two-component fermions.

References

[1] S. Sugawa, K. Inaba, S. Taie, R. Yamazaki, M. Yamashita, and Y. Takahashi, *Interaction and filling-induced quantum phases of dual Mott insulators of bosons and fermions*, Nat. Phys. **7**, 642 (2011).
[2] K. Noda, R. Peters, N. Kawakami, and Th. Pruschke, *Many-body effects in a Bose-Fermi mixture* Phys. Rev. A **85**, 043628 (2012).

Towards Russian optical clock with cold strontium atoms, present status and performance

Sergey Slusarev[1], Alex Kostin[1], Slava Barychev[1], Kseniya Khabarova[1], Sergey Strelkin[1], Sergey Donchenko[1], Vitaly Palchikov[1,*], and Andrey Krasavin[2]

1. National Research Institute for Physical-Technical and Radiotechnical measurements, Moscow Region, Russia
2. National Reseach Nuclear University « MEPHI », Moscow, Russia
**vitpal@mail.ru*

Neutral strontium is an interesting candidate for the realization of an optical clock using a magic-wavelength optical lattice to store the atoms. I this poster, we will report on our work towards the development of an optical lattice clock using Sr atoms in the VNIIFTRI. As the first step for the realization of proposed optical clock, we have efficiently cooled and trapped atoms in a blue magneto-optical trap (MOT) employing a Zeeman slower. The first stage MOT is operated on the $^1S_0$- $^1P_1$ transition at 461 nm. It was demonstrated, that the number of strontium atoms were substantially increased using the 679 nm and 496 nm repamping diode lasers. The Sr –MOT is operative and the first observation of cold atoms is reported. The experimental set-up with ULE –cavity and error signals are discussed.

Reference

[1] S. Slusarev *et al.*, Proc. of joint Conference of the IEEE International Control Symposium & European Frequency and Time Forum, May 1-5, San Francisco, California, pp. 736-738 (2011).

Lattices of atom microtraps on magnetic-film atom chips

A. L. La Rooij, V. Y. F. Leung, A. Tauschinsky, and R. J. C. Spreeuw

Van der Waals-Zeeman Instituut,
Institute of Physics, Universiteit van Amsterdam

We discuss the latest progress of our experiments with atomic microclouds on a magnetic-film atom chip [1]. So far we have demonstrated a shift register, atom number squeezing close to quantum degeneracy [2], and spatially resolved, coherent excitation of Rydberg atoms [3]. A recently installed next-generation chip facilitates the continuation of our experiments at trap separations of 10 μm. Also our improved imaging setup is presented. We aim to measure Rydberg-Rydberg Interactions between different microclouds to make quantum gates. Scaling down even further, we propose to aim for mesoscopic ensemble qubits in a 5 μm lattice, and for direct quantum simulators using sub-optical lattices of 100 nm period [4].

References

[1] Whitlock *et al.*, New J. Phys. **11**, 023021 (2009).
[2] Whitlock *et al.*, PRL **104**, 120402 (2010).
[3] Tauschinsky *et al.*, PRL **81**, 063411 (2010).
[4] Leung *et al.*, Quantum Inf. Process. **10**, 955 (2011).

Controlled emission and absorption of single photons by a single ion

Michael Schug[1,*], Jan Huwer[1,2], Joyee Ghosh[1,2], Christoph Kurz[1], Philipp Müller[1], Nicolas Piro[2], Francois Dubin[2], and Jürgen Eschner[1,2]

1. Experimentalphysik, Saarland University, Saarbrücken, Germany
2. ICFO – Institut de Ciences Fotoniques, Barcelona, Spain
**mschug@physik.uni-saarland.de*

We study emission and absorption of single photons by a single atom as the fundamental processes in quantum information technology. We observe the absorption of single resonant photons from an 854 nm SPDC photon pair source by a single Ca^+ ion, heralded by the detection of the partner photon. Photon absorption induces a quantum jump in the ion in coincidence with the arrival of the partner photon [1]. Moreover, we prepare the ion as a polarization-selective absorber with adjustable basis, and show that the heralded absorption reveals the entanglement of the photon pairs; this is a prerequisite of photon-to-atom entanglement transfer [2]. We also generate resonant single 854 nm photons by controlled emission from a single ion into a single optical mode at ~ 3000 s^{-1} rate. We currently investigate the transmission of these photons and their resonant absorption in a second ion at 1 m distance, enabling distant entanglement between the ions [3].

References

[1] N. Piro *et al.*, “Heralded single-photon absorption by a single atom”, DOI:10.1038/nphys1805.
[2] J. Huwer *et al.*, arXiv: 1111.1085.
[3] S. Ritter *et al.*, arXiv: 1202:5955.

Amelioration of BB84 Quantum transmission protocol based on Blind detection method

Mohammed Abdedaim* and Skander Aris

Department of Electronics, University of Mentouri, Constantine, Algeria
**m.abdedaim@hotmail.fr*

We report on the development of a Quantum Cryptographic Networks for an approach to more secure communications, including a BB84 protocol and Blind detection method. Information is encoded in quantum bits (qubits), intrinsic physical properties, such as polarization of a photon. Quantum physics allows encoding information using the correlation between two or more particles. Quantum Key Distribution (QKD) is one of the innovative methods of information processing that emerged from the properties of «superposition of states» and «entanglement». QKD is used before classical information is transmitted over conventional non-secure communication channels like phone lines and optical fiber networks. Since quantum physics laws state that a single particle like a photon cannot be split or cloned, it certifies the absolute security of communication. In fact, quantum links are combined with fiber counterparts could extend secure communication between points on earth to a global level. Our proposed paper presents a blind detection algorithm for linear mixtures of sources and therefore can be applied to systems of mobile communications. However, in our study it is used for coding and decoding quantum transmissions. The essential aim of our implementation is to present an example of application for single secure optical communication using BB84. We expect future applications of this method in quantum communications such as quantum transmission satellite to each other or satellite to ground station. Our work is a part of approach study and idea to product Quantum Error Correction Algorithm Control in LEO satellite quantum communications that is ongoing under the different Space Agency in the world.

Einstein-Podolsky-Rosen entanglement and quantum steering for a BEC

Bogdan Opanchuk, Qiongyi He, Peter Drummond, and Margaret Reid

CAOUS Centre for Atom Optics, Swinburne University of Technology, Melbourne, Australia
**qiongyihe@swin.edu.au*

We analyse how to generate multi-particle Einstein-Podolsky-Rosen (EPR) entanglement [1] between groups of atoms in a double-well Bose-Einstein condensate. We consider both the statistics of the ground state and that of dynamical evolution, with two internal modes at each well, so that the entanglement can be detected as a reduction in the variances of the sums of local Schwinger EPR spin observables [2]. The local nonlinear S-wave scattering interaction creates a spin squeezing at each well, while the tunneling introduces an interference that results in an inter-well entanglement. The entanglement increases with atom number, and becomes sufficiently strong at higher numbers that the EPR paradox and steering nonlocality [3] can be realised. Our predictions are based on a full quantum solution and, for larger numbers, a truncated Wigner function simulation using a multi-mode model. We explain how the strategy can be extended to generate genuine tripartite entanglement among three wells.

References

[1] A. Einstein, B. Podolsky, and N. Rosen, *Can Quantum-Mechanical description of physical reality be considered complete?*, Phys. Rev. **47**, 777 (1935).
[2] Q. Y. He *et al.*, *Einstein-Podolsky-Rosen Entanglement Strategies in Two-Well Bose-Einstein Condensates*, Phys. Rev. Lett. **106**, 120405 (2011).
[3] D. H. Smith *et al.*, *Conclusive quantum steering with superconducting transition-edge sensors* Nat. Commun. **3**, 625 (2012).

Four-partite cluster states and their application for quantum teleportation

Olesya V. Belyaeva and Anatoly S. Chirkin

Faculty of Physics, M. V. Lomonosov Moscow State University, Moscow, Russia
lisenok.msu@gmail.com

There are two ways to generating multipartite entangled states: in gaseous and in condensed matter. In the latter, generation of entangled photon states is based on optical parametric down-conversion. Other way of creating the multipartite entanglement is the atom-field one. We study quantum properties of cluster four-partite state for continuous variables. The cluster state under consideration can be generated both in gas [1] and in aperiodical nonlinear photonic crystals [2]. They are described by the identical interaction Hamiltonian. We also study teleportation of two-mode entangled CV state using the cluster state; the teleportation fidelity is computed.

References

[1] X. Liang, X. Hu, C. He "Creating multimode squeezed states and GXZ entangled states using atomic coherence effects" Phys. Rev. A **85,** 032329 (8pp) (2012).
[2] O. V. Belyaeva, A. S. Chirkin "Statistical properties of four-mode quantum states in coupled optical parametric down-conversions" J. Russian Laser Research, **30**, 499-507 (2009).

Heralded noiseless linear amplifier in continuous variable QKD

Rémi Blandino[1], Anthony Leverrier[2], Marco Barbieri[1], Jean Etesse[1], Philippe Grangier[1], and Rosa Tualle-Brouri[1,3]

1. Laboratoire Charles Fabry, IOGS-CNRS, Université Paris-Sud, Campus Polytechnique, RD 128, 91127 Palaiseau cedex, France
2. ICFO-Institut de Ciencies Fotoniques, Av. Carl Friedrich Gauss 3, 08860 Castelldefels, Barcelona, Spain
3. Institut Universitaire de France, 103 boulevard St. Michel, 75005, Paris, France
**remi.blandino@institutoptique.fr*

Quantum key distribution (QKD) consists of distributing a secret key to two distant parties in an untrusted environment controlled by an adversary. Among QKD protocols, those encoding information in the amplitude and phase of coherent states provide interesting performances and implementation [1]. However, due to losses or noise of the quantum channel, there exist a maximum transmission distance for which the secret key rate drops to zero. In this work [2], we consider the use of a linear noiseless amplifier [3], which has the interesting property of amplifying the signal without amplifying the noise, in order to increase the performances of the QKD. We show that the maximum distance of transmission can be increased using thisdevice, as well as the maximum tolerable noise.

References

[1] F. Grosshans *et al.*, Nature **421**, 238Ð241 (2003).
[2] R. Blandino *et al.*, arXiv:1205.0959 (2012).
[3] F. Ferreyrol *et al.* , Phys. Rev. Lett. **104**, 123603 (2010).

Observation of quantum superposition state without wave function collapse

Minaru Kawamura[1,*], Tatsuya Mizukawa[2], Kosuke Araki[3], and Ryouhei Kunitomi[3]

1. Electrical and Electronic Engineering, Okayama University of Science, Okayama, Japan
2. Graduate School of Engineering, Okayama University of Science, Okayama, Japan
3. School of Engineering, Okayama University of Science, Okayama, Japan
**minaru@ee.ous.ac.jp*

We present a paradox that coherence transfer to macroscopic quantum pure state allows amplification of the coherence, and which may violate the no-cloning theorem. It is also shown that the wave function collapse during observation can be explained with decoherence while pure states shift to mixed states through interaction with macroscopic body in mixed states.

Reference

[1] Quantum Measurement, Vladimir B. Braginsky and Farid Ya. Khalili, "Quantum measurement" (Cambridge university press 1992).

Neutral atom qubits in a planar lattice of magic ground-Rydberg traps

M. Piotrowicz, G. Li, K. Maller, S. Zhang, M. Lichtman, and M. Saffman

Department of Physics, University of Wisconsin, Madison, WI, 53706, USA

We have loaded single Cs atoms into a planar array of blue detuned optical traps. The array is created using a novel optical beam arrangement that creates an intrinsically 2D array, is phase stable, and suitable for magic trapping of ground and Rydberg states [1]. We demonstrate single qubit gates in the array, and show that Rydberg excited atoms can be trapped. The array forms the basis for experiments with several atomic qubits and Rydberg gates. Work supported by IARPA, ARO, and DARPA.

Reference

[1] S. Zhang, F. Robicheaux, and M. Saffman, *Magic-wavelength optical traps for Rydberg atoms*, Phys. Rev. A **84**, 043408 (2011).

Long-lived ion qubits in a microfabricated surface trap

Peter Maunz*, Soyoung Baek, Stephen Crain, Daniel Gaultney, Rachel Noek,
Emily Mount, Andre van Rynbach, and Jungsang Kim

Duke University, Durham, North Carolina, USA
**Peter@maunz.name*

A chain of trapped ion qubits together with Coulomb mediated two-qubit gates is a promising way to construct a modest-size quantum register. Quantum logic gates can also be performed between two remote ions using photon-mediated entanglement [1], which leads to the possibility of connecting two remote chains together to form a larger quantum information processor. These two physical mechanisms can be used to realize a quantum computer architecture where multiple ion chains are interconnected through a recon?gurable all-optical network [2].

Silicon microfabrication technology can be used to design and fabricate scalable surface trap structures. Here, we trap a single ytterbium-171 ion in a surface trap made by Sandia National Laboratories [3]. We use an off-resonant picosecond pulsed laser with stabilized repetition rate to drive Raman transitions between the hyperfine qubit states. Ramsey interferometry demonstrates a coherence time of more than 1.5s.

References

[1] P. Maunz et al., Phys. Rev. Lett. **102**, 250502 (2009).
[2] J. Kim and C. Kim, Quant Inf. Comput. **9**, 0181 (2009).
[3] D. T. C. Allcock et al., Applied Physics B 10.1007/s00340-011-4788-5 (2011).

Nonclassicality indicators for entangled number states

Siamak Khademi*, Elham Motaghi, and Parvin Sadeghi

Department of Physics, University of Zanjan, Zanjan, Iran
**khademi@znu.ac.ir & siamakkhademi@yahoo.com*

Recently a nonclassicality indicator is introduced which is based on the interference of quantum states in phase space quantum mechanics [1]. It is applied for some real distribution functions. Kenfack and Życzkowski[2] had also defined a non classicality indicator based on the amount of negativity in Wigner function. Here, we applied these nonccassicality indicators for entangled state of two eigenstate of Harmonic oscillator in the Wigner, Husimi and Rivier representations. The maximum of nonclassicality indicator is happen for pseudo bell states and the behavior of nonclassicality indicators are compared with the entanglement of formation.

References

[1] P. Sadeghi, S. Khademi and S. Nasiri; "Nonclassicality Indicator for the Real Phase-space Distribution Functions"; Phys. Rev. A, **82**, pp 012102 (2010).
[2] A. Kenfak and. K. Zyczkowski; "Negativity of the Wigner function as an indicator of nonclassicality"; *J. Opt. B: Quantum Semiclass. Opt.* **6**, pp 396-404 (2004).

Remote entanglement between a single atom and a BEC

M. Lettner, M. Mücke, S. Riedl, C. Vo, C. Hahn, S. Baur, J. Bochmann, S. Ritter, S. Dürr, and G. Rempe

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Entanglement between stationary systems at remote locations is a key resource for quantum networks. We report on the experimental generation of remote entanglement between a single atom inside an optical cavity and a Bose-Einstein condensate (BEC) [1]. To produce this, a single photon is created in the atom-cavity system, thereby generating atom-photon entanglement. The photon is transported to the BEC and converted into a collective excitation in the BEC, thus establishing matter-matter entanglement. After a variable delay, this entanglement is converted into photon-photon entanglement. The matter-matter entanglement lifetime of 100 µs exceeds the photon duration by two orders of magnitude. The total fidelity of all concatenated operations is 95 %. This hybrid system opens up promising perspectives in the field of quantum information. The performance of the system is limited by the atom-cavity system. The BEC as a quantum memory is characterized in [2].

References

[1] M. Lettner, M. Mücke, S. Riedl, C. Vo, C. Hahn, S. Baur, J. Bochmann, S. Ritter, S. Dürr, and G. Rempe, *Remote entanglement between a single atom and a Bose-Einstein condensate*, Phys. Rev. Lett. **106**, 210503 (2011).
[2] S. Riedl, M. Lettner, C. Vo, S. Baur, G. Rempe, and S. Dürr, *Bose-Einstein condensate as a quantum memory for a photonic polarization qubit*, Phys. Rev. A **85**, 022318 (2012).

Spatial entanglement in two-electron atomic systems

Yew Kam Ho*, Yen-Chang Lin, and Chih-Yuan Lin

Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan 106
**ykho@pub.iams.sinica.edu.tw*

Recently, there have been considerable interests to investigate quantum entanglement in two-electron model atoms ([1-3] and references therein). Here we investigate quantum entanglement for the ground and excited states of two-electron atomic systems using correlated wave functions. We study the spatial entanglement of such systems, concentrating on the particle-particle entanglement coming from the continuous spatial degrees of freedom. We use two-electron wave functions constructed by employing *B*-spline basis to calculate the linear entropy of the reduced density matrix $L = 1 - Tr_A(\rho_A^2)$. Here $\rho_A = Tr_B(|\varphi\rangle_{AB\ AB}\langle\varphi|)$ is the one-electron reduced density matrix obtained after tracing the two-electron density matrix over the degrees of freedom of the other electron. For the helium atom (Z = 2), we have calculated the linear entropy for the ground state and the 1*sns* $^1S^e$ (n = 2 – 10) excited states. Results are compared with other calculations in the literature [1-3].

References

[1] J. P. Coe and I. D'Amico, *J. Phys.: Conf. Ser.* **254**, 012010 (2010).
[2] D. Manzano *et. al.*, *J. Phys. A: Math. Theor.* **43**, 275301 (2010).
[3] J. S. Dehesa *et. al.*, *J. Phys. B* **45**, 015504 (2012).
Acknowledgments: YKH is supported by National Science Council of Taiwan.

Nonlinear interferometer and multipartite entanglement using two four wave mixing amplifiers

Jietai Jing*, Jia Kong, Zhongzhong Qin, Hailong Wang, F. Hudelist, Z. Y. Ou, and Weiping Zhang

State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai, China
**jtjing@phy.ecnu.edu.cn*

Optical interferometer is the basis for precision measurement. We report on an experiment in which we construct a nonlinear interferometer with four wave mixing amplifiers acting as beam splitters to split and recombine an incoming optical field. The interferometer can in principle have 100% visibility. Since amplification is actively involved in the interferometer, the phase sensing field inside the interferometer is amplified from the input field and so is the output field exhibiting the interference fringe. Thus, the sensitivity can be greatly enhanced as compared to the traditional linear interferometer [1, 2]. The quantum correlation between multiple beams is very important for constructing a real quantum network and precision measurement [3]. Thus, we also explored the several possibilities for achieving quantum correlation among multiple beams in such system.

References

[1] B. Yurke, S. L. McCall, and J. R. Klauder, "SU(2) and SU(1,1) interferometers," Phys. Rev. A33, 4033 (1986).
[2] Jietai Jing, Cunjin Liu, Zhifan Zhou, Z. Y. Ou, and Weiping Zhang, "Realization of a nonlinear interferometer with parametric amplifiers," Appl. Phys. Lett. 99, 011110 (2011).
[3] P. van Loock and S. L. Braunstein, Phys. Rev. Lett. "Multipartite Entanglement for Continuous Variables: A Quantum Teleportation Network" 84, 3482(2000).

On a systematic degenerate adiabatic perturbation theory

Gustavo Rigolin[1,]* and Gerardo Ortiz[2]

1. Departamento de Física, Universidade Federal de São Carlos, São Carlos, SP 13565-905, Brazil
2. Department of Physics, Indiana University, Bloomington, IN 47405, USA
**rigolin@ufscar.br*

We present a degenerate adiabatic perturbation theory (DAPT) for quantum systems whose Hamiltoninans possess degenerate eigenvalues [1]. Its goal is to solve the time dependent Schrödinger equation, with the zeroth order being the quantum adiabatic approximation, in terms of a power series expansion built on a small parameter that is related to the inverse of the time it takes to drive the system's Hamiltonian from its initial to its final form. As an application, DAPT leads to the derivation of rigorous conditions for the validity of the adiabatic theorem of quantum mechanics for degenerate systems [2]. The same formalism can be used to find non-adiabatic corrections to the non-Abelian Wilczek-Zee geometric phase [1]. These corrections are relevant to assess the validity of the practical implementation of the concept of fractional exchange statistics. We illustrate the formalism by exactly solving a time-dependent problem and comparing its solution to the perturbative one and also by studying several problems numerically solved.

References

[1] G. Rigolin and G. Ortiz, *Adiabatic Perturbation Theory and Geometric Phases for Degenerate Systems*, Phys. Rev. Lett. **104**, 170406 (2010).
[2] G. Rigolin and G. Ortiz, *The Adiabatic Theorem for Quantum Systems with Spectral Degeneracy*, eprint arXiv:1111.5333v1 [quant-ph].

Efficient atomic excitation by multi-photon pulses propagating along two spatial modes for quantum information processing

Jiří Minář[1,*], Yimin Wang[1], and Valerio Scarani[1,2]

1. Centre for Quantum Technologies, National University of Singapore, Singapore
2. Department of Physics, National University of Singapore, Singapore
**cqtjm@nus.edu.sg*

Efficient coupling between a single atom and light lies at the heart of scalable quantum networks, where the photon as "flying qubit" transfers the information to the "stationary qubit" - the atom. We investigate the dynamics of a single two-level atom, which interacts with pulses propagating in two spatial-modes (odd and even) and frequency-continuum, a setup particularly relevant for applications in integrated quantum optical devices. We discuss the single and multi-photon pulse properties maximizing the atomic excitation. We show that the maximum atomic excitation probability with multi-photon pulses in the even-mode is a monotonic function of the average photon number for coherent state, but not for Fock states. Furthermore, we demonstrate that the atomic dynamics can be controlled by the relative phase between the two counter-propagating coherent state pulses incident on the atom.

Reference

[1] Y. Wang, J. Minář and V. Scarani, "State-dependent atomic excitation by multi-photon pulses propagating along two spatial modes", arXiv:1204.5265 (2012).

Topological protection in photonic systems

M. Hafezi[1,*], J. Fan[1], J. Chen[1], E. Demler[2], M. Lukin[2], J. Taylor[1], and A. Migdall[1]

1. Joint Quantum Institute, NIST/UMD, College Park 20742, USA
2. Harvard University, Cambridge MA 02138, USA
**Hafezi@umd.edu*

Topological properties of physical systems can lead to natural protection against perturbations. In electronic systems, this robustness is exemplified by quantized conductance and edge state transport in the quantum Hall effects. Here we demonstrate how various quantum spin Hall Hamiltonians can be simulated with linear optical elements using a two dimensional network of coupled optical resonators. Key features of quantum Hall systems, including the characteristic Hofstadter butterfly and robust edge state transport, can be obtained in such systems. We experimentally investigate the implementation of such ideas in silicon-on-insulator technology and their application as an optical delay line. Such systems allow the presence of photonic edge states, which are insensitive to disorder, caused by fabrication errors. Furthermore, the addition of an optical non-linearity to our proposed system leads to the possibility of implementing a fractional quantum Hall state of photons, where phenomenon such as fractional statistics may be observable.

Exploring cavity-mediated long-range interactions in a dilute quantum gas

R. Landig, R. Mottl, F. Brennecke, K. Baumann, T. Donner, and T. Esslinger

Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland
**esslinger@phys.ethz.ch*

We report on the observation of a characteristic change in the excitation spectrum of a Bose-Einstein condensate and increased density fluctuations due to cavity-mediated long-range interactions. Increasing the strength of the interaction leads to a softening of an excitation mode at a finite momentum, preceding a superfluid to supersolid phase transition. The observed behavior is reminiscent of a roton minimum, as predicted for quantum gases with long-range interactions [1]. We create long-range interactions in the BEC using a non-resonant transverse pump beam which induces virtual photon exchange via the vacuum field of an optical cavity. The mode softening is spectroscopically studied across the phase transition using a variant of Bragg spectroscopy. At the phase transition a diverging density response is observed which is linked to increased density fluctuations. Using the openness of the cavity we monitor these fluctuations in-situ and identify the influence of the quantum measurement backaction.

Reference

[1] Mottl *et al.*, arXiv: 1203.1322.

Non-Markovian waiting time distribution

Kimmo Luoma[1,*], Kari Härkönen[2], Sabrina Maniscalco[1,3], Kalle-Antti Suominen[1], and Jyrki Piilo[1]

1. Turku Centre for Quantum Physics, Department of Physics and Astronomy, University of Turku, FI-20014, Turun yliopisto, Finland
2. Max-Planck-Institute für Physik Komplexer Systeme, Nöthnitzner strasse 38, D-01187 Dresden, Germany
3. SUPA, EPS/Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK
**ktluom@utu.fi*

Simulation methods based on stochastic realizations of state vector evolutions are commonly used tools to solve open quantum system dynamics, both in the Markovian and non-Markovian regime. Here, we address the question of waiting time distribution (WTD) of quantum jumps for non-Markovian systems. We generalize Markovian quantum trajectory methods in the sense of deriving an exact analytical WTD for non-Markovian quantum dynamics and show explicitly how to construct this distribution for certain commonly used quantum optical systems [1].

Reference

[1] K. Luoma, K. Härkönen, S. Maniscalco, K.-A. Suominen and J. Piilo *Non-Markovian waiting time distribution*, to be submitted.

Line shapes in electromagnetically induced transparency for $5S_{1/2}$ –$5P_{3/2}$–$5D_{5/2}$ transitions of ^{87}Rb atoms

Heung-Ryoul Noh[1,*], Eun Hyun Cha[1], and Han Seb Moon[2]

1. Department of Physics, Chonnam National University, Gwangju 500-757, Korea
2. Department of Physics, Pusan National University, Busan 609-735, Korea
**hrnoh@chonnam.ac.kr*

We present an accurate calculation and discrimination of the electromagnetically induced transparency for the $5S_{1/2}$–$5P_{3/2}$–$5D_{5/2}$ transition of ^{87}Rb atoms. Considering all possible transitions, time–dependent density matrix equations were set up for six polarization configurations of the lasers, and solved numerically. The solved density matrix elements were then averaged over the Maxwell-Boltzmann velocity distribution and various transit times. In particular, we could discriminate the contribution of one-photon and two-photon resonance effects in the calculated spectra. We found that the signals for the $5D_{5/2}(F'' = 2,3)$ states were mostly composed of the mixed term, whereas the signal for the $5D_{5/2}(F'' = 4)$ state was originated from both the pure two-photon resonance term and the mixed term [1].

Reference

[1] H. R. Noh and H. S. Moon, *Transmittance signal in real ladder-type atoms*, Phys. Rev. A **85**, 033817 (2012).

Long lived polaritons confined in a tunable Fabry-Perot microcavity

Benjamin Besga[1], Jakob Reichel[1], Jérôme Estève[1,*],
Andreas Reinhard[2], Javier Miguel-Sanchez[2], Thomas Volz[2], and Atac Imamoglu[2]

1. Laboratoire Kastler Brossel, CNRS/ENS/UPMC, Paris, France
2. Institute of Quantum Electronics, ETH Zurich, Zurich, Switzerland
**esteve@lkb.ens.fr*

Semiconductor microcavity polaritons offer new opportunities to study the properties of interacting bosons in the quantum degenerate regime. Here, we present a novel experimental platform to produce trapped polaritons with potentially long lifetimes. Ourcavity is a fiber Fabry–Perot cavity [1] formed between a concave mirror at the tip of a fiber and a planar semiconductor Bragg mirror located below the quantum well. With a single quantum well, we observe strong coupling to the cavity as witnessed by an avoided level crossing as a function of cavity detuning. For multiple quantum wells, the system exhibits signatures of polariton lasing observed through pump-power dependence, blue-shift and linewidth narrowing at threshold. One particular feature of our setup is the possibility to realize high Q values (> 70000). In principle, this should allow for the realization of tightly confined polaritonic Bose-Einstein condensates with a decay time much longer than the polariton thermalization rate.

Reference

[1] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, and J. Reichel, *A fiber Fabry–Perot cavity with high finesse*, New J. Phys. **12**, p. 065038 (2010).

Generation and tomography of W-states in an atomic spin-ensemble coupled to a high-finesse cavity

Florian Haas*, Jürgen Volz, Roger Gehr, Jakob Reichel, and Jérôme Estève

Laboratoire Kastler-Brossel, CNRS, UPMC, ENS, Paris, France
**Florian.Haas@ens.fr*

We report the scalable generation of W-states (Dicke states of first order) encoded in the hyperfine structure of neutral ^{87}Rb-atoms in a high-finesse fiber Fabry-Perot cavity. We prepare an ensemble of atoms in the hyperfine state $|F=1\rangle$ and apply a weak microwave pulse resonant to the transition $|F=1\rangle \rightarrow |F=2\rangle$, which leads to the transfer of a single atom to $|F=2\rangle$ with a probability p=0.2. We then detect if there is an atom in $|F=2\rangle$ by probing the cavity and repeat the sequence if it was not succesful. The use of the cavity allows detection with high fidelity and negligible spontaneous emission [1], thus preventing the destruction of the entangled state. To quantify the entanglement, we havedeveloped a new tomography method that also makes use of the cavity detection and allows to measure the Husimi-Q distribution, from which we reconstruct the density matrix of the prepared state. W-states consisting of 6, 11, 25 and 42 atoms were created with a fidelity of approx. 30%.

Reference

[1] J. Volz, R. Gehr, J. Estève and J. Reichel, *Measurement of the internal state of a single atom without energy exchange*, Nature **475**, pp. 210-213 (2011).

Generating non-classical light using Rydberg interactions

Valentina Parigi, J. Stanojevic, E. Bimbard, A. Ourjoumtsev, and P. Grangier

Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris-Sud, 2 av. Augustin Fresnel, 91127 Palaiseau cedex, France

We study, both theoretically and experimentally, the possibility to use an ensemble of cold Rydberg atoms as a strongly non-linear optical medium which could enable strong photon-photon interactions and the deterministic generation non classical states of light. The quantum state of a light beam can be stored in an ensemble of cold atoms as a polarisation wave involving two long-lived atomic states. If one of these atomic states is a Rydberg state, this polariton will evolve due to long-range atomic interactions. As a result, a coherent pulse of light stored in the atomic medium should turn into a non-classical polaritonic state which could be retrieved as a pulse of non-classical light. We have theoretically shown that the Rydberg gas should act as "quantum scissors" on the stored quantum state, and the retrieved optical pulse should become a coherent superposition of zero and one photons presenting a non-classical, negative Wigner function [1]. We have also found realistic experimental parameters to retrieve this pulse with a high efficiency in a well-defined spatial and temporal mode, which should make the non-classical properties of the state observable in a homodyne measurement [2]. As a first step in this direction, we are experimentally investigating the non-linear optical susceptibility of a Rydberg cloud in a classical regime.

References

[1] J. Stanojevic, V. Parigi, E. Bimbard, A. Ourjoumtsev, P. Pillet, P. Grangier, arXiv:1203.6764v1.
[2] J. Stanojevic, V. Parigi, E. Bimbard, R. Tualle-Brouri, A. Ourjoumtsev, P. Grangier, Phys. Rev. A **84**, 053830 (2011).

Quantum noise for Faraday light-matter interfaces

D. V. Vasilyev[1,*], K. Hammerer[1], N. Korolev[2], and A. S. Sørensen[2]

1. ITP and AEI, Leibniz Universität Hannover, Germany
2. Niels Bohr Institute, QUANTOP, Copenhagen, Denmark
**denis.vasilyev@itp.uni-hannover.de*

In light matter interfaces based on the Faraday effect quite a number of quantum information protocols have been successfully demonstrated. In order to further increase the performance and fidelities achieved in these protocols a deeper understanding of the relevant noise and decoherence processes needs to be gained. In this work [1] we provide for the first time a complete description of the decoherence from spontaneous emission. We derive from first principles the effects of photons being spontaneously emitted into unobserved modes. Our results relate the resulting decay and noise terms in effective equations of motion for collective atomic spins and the forward propagating light modes to the full atomic level structure. We illustrate and apply our results to the case of a quantum memory protocol. Our results can be applied to any Alkali atoms, and the general approach taken in this article can be applied to light matter interfaces and quantum memories based on different mechanisms.

Reference

[1] arXiv:1112.5394v2 (it is about to appear in special issue of Journal of Physics B: Atomic, Molecular & Optical Physics).

Interaction of light-quantized pulse with atomic system

S. Derouault* and M. A. Bouchene

Laboratoire Collisions Agrégats Réactivité, C.N.R.S UMR 5589, IRSAMC, Université Paul Sabatier
**derouault@irsamc.ups-tlse.fr*

We explore the interaction between an atom and a quantized pulse in the arbitrary coupling strength regim. Two complementary situations are studied both theoretically and numerically. In the first a propagating one-photon wave packet interacts with an atom located in a one-dimensional waveguide, and in the second situation an atom pass through a single mode detuned micromaser cavity. In the former case we show that the one photon wave packet experienced a temporal reshaping leading its algebraic area to vanish. A Schrödinger approach is used and an interpretation in the spectral domain is given. In the latter case we highlight the importance of non-adiabatic coupling, that depends on the mode shape, and their interplay with the (quantized) atomic motion. We show that the transfer of population can be modulated by varying the atomic velocity. An analogy with a Michelson interferometer is exhibited.

References

[1] J. Gillot and M. A. Bouchene, *Complete population transfer induced by transient nonadiabatic effects in a strongly detuned micromaser*, JOSA B, **28**, pp. 1324-1327 (2011).
[2] S. Derouault and M. A. Bouchene, *Pulse area theorem for one photon wavepacket interacting with a two-level atom in a waveguide*, submitted to Phys. Rev. A (2012).

Strong coupling of single atoms to a whispering-gallery-mode bottle microresonator

Jürgen Volz*, Danny O'Shea, Christian Junge, and Arno Rauschenbeutel

Institute for Atomic and Subatomic Physics, Vienna University of Technology, Vienna, Austria
**jvolz@ati.ac.at*

We describe our recent results demonstrating strong coupling between single rubidium atoms and a high-Q whispering-gallery-mode bottle microresonator (Q = 50 million)[1]. We observe clear signals of individual atoms passing through the resonator mode with interaction times of several microseconds. Given this brief interaction time, we have implemented a real-time atom detection/probing scheme to enable experiments on this timescale. We investigate the light transmission and reflection characteristics of the atom-resonator system. Our experimental results show a strong interaction between the atom and the resonator, which is observed by the large change in light transmission through the coupling fibers.

As an application of this system, we describe our progress towards the realization of a four-port device capable of routing photons between two optical nanofibers coupled to the resonator mode. Financial support by the DFG, the Volkswagen Foundation, and the ESF is gratefully acknowledged.

Reference

[1] D. O'Shea, C. Junge, M. Pöllinger, A. Vogler, and A. Rauschenbeutel, *All-optical switching and strong coupling using tunable whispering-gallery-mode microresonators*, Appl. Phys. B, **105**, 1, 129 (2011).

Excitation of a single atom with a temporaly shaped light pulses

Syed Abdullah Aljunid[1,2], Dao Hoang Lan[3], Yimin Wang[1], Gleb Maslennikov[1,*], Valerio Scarani[1,4], and Christian Kurtsiefer[1,4]

1. Centre for Quantum Technologies, National University of Singapore
2. Univirsité Paris Nord, Paris, France
3. Physics Department, University of Twente, Twente, Netherlands
4. Physics Department, National University of Singapore
**cqtmg@nus.edu.sg*

We investigate the interaction between a single ^{87}Rb atom and optical pulses with a controlled temporal envelope [1]. We prepare optical pulses with rising exponential and rectangular temporal profiles and couple them to an atom with high NA lens. We have found that an atom is excited faster by using less photons in a driving pulse with a rising exponential shape. Although a rectangular shape eventually leads to higher excitation probability it takes more photons to excite the atom. We also observe that the atomic transition can be saturated with approximately 100 photons in a pulse. This suggests that one expects to see a nonlinear interaction between atom and light for such low photon number. Indeed, by increasing photon number to ≈ 1000 we observe Rabi oscillations with ≈ 100 MHz. This result show a possibility of optical switching for low photon numbers without cavity assistance.

Reference

[1] Y. Wang et. al., *Efficient excitation of a two level atom by a single photon in a propagating mode*, Phys. Rev. A. **79**, 011402(R) (2011).

Mechanical resonance imaging and optomechanical coupling of atoms in a intracavity trichromatic lattice

Daniel Brooks[1,*],Thierry Botter[1], Sydney Schreppler[1], Nathan Brahms[1], and Dan Stamper-Kurn[1,2]

1. Department of Physics, University of California, Berkeley, CA 94720, USA
2. Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
**dwb@berkeley.edu*

Complex designer potentials for ultracold atoms can be created by combining optical lattices, and have great utility for simulations of condensed matter systems. Here, using optomechanical interactions, we spectrally resolve atoms at individual sites of asuperlattice with site dependent mechanical resonance frequencies. This allows us to make a "mechanical resonance image", mapping the atomic distribution and lattice geometry. Further, the optomechanical coupling creates infinite-range interactions between motion of atoms at spatially disparate sites. This systems acts as a coupled array of quantum mechanical resonators with implementable entanglement and state-transfer operations.

Local fields and renormalization of characteristic frequencies for light emitters in a dielectric

Maxim Gladush[1,*] and Dmitry Kuznetsov[2]

1. Institute for Spectroscopy of the Russian Academy of Sciences, Fizicheskaya Str. 5, Troitsk, Moscow region, 142190, Russia
2. State research center of Russian Federation, Troitsk Institute for Innovation and Fusion Research, TRINITI, Troitsk, Moscow region, 142190, Russia
**mglad@isan.troitsk.ru*

The macroscopic and microscopic quantum theories are known to give corrections to the rate of spontaneous emission in a dielectric. At the same time, there are only few works that provide Maxwell-Bloch-type equations for embedded particles derived using ab initio techniques. Another problem is that competing theories often give conflicting results while experiments tend to aggravate the confusion. We study how a continuous dielectric medium that fills the space between quantum light emitters may influence their interaction with external laser fields and modify their radiative properties. A generalized master equation is derived for two-level emitters, which form an ensemble of optical centers in a dielectric. The equation contains the effective values of the acting pump field and the radiation relaxation rate of the optical center. The formalism represents a fully microscopic approach and is based on a BBGKY hierarchy for reduced density matrices and correlation operators of material particles and field modes. The method allows one to avoid phenomenological procedures when taking into account the effects of individual and collective behavior of the emitters associated with the presence of intermediate environment. The analytical expressions for the excitation lifetime of an optical center are shown to be in agreement with several experiments. The similarities and differences with the other existing theories are discussed.

Dynamics of atom-atom correlations in the Fermi model

Massimo Borrelli[1,*], Carlos Sabín[2], Gerardo Adesso[3], Francesco Plastina[4,5], and Sabrina Maniscalco[1,6]

1. SUPA, EPS/Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK
2. Instituto de Física Fundamental, CSIC, Serrano 113-B, 28006 Madrid, Spain
3. School of Mathematical Sciences, The University of Nottingham, University Park, Nottingham NG7 2RD, UK
4. Dipartimento di Fisica, Università della Calabria, 87036 Arcavacata di Rende (CS), Italy
5. INFN–Gruppo Collegato di Cosenza, Italy
6. Turku Center for Quantum Physics, Department of Physics and Astronomy,University of Turku, FIN20014, Turku, Finland
**mb325@hw.ac.uk*

In this work we study the dynamics of several types of atom-atom correlations in the famous two-atom Fermi problem [1]. Although any causality issue regarding quantum mechanical probabilities in such a model was recently solved in [2], the influence of micro-causality on correlations behavior is still an open subject of investigaition.

References
[1] E. Fermi, Rev. Mod. Phys. **4**, 87 (1932).
[2] C. Sabín, M. del Rey, J. J. García-Ripoll, and J. León, Phys. Rev. Lett **107**, 150402 (2011).

Coupling color centers in diamond to fiber-based Fabry-Pérot microcavities

Hanno Kaupp[1,2,*], Matthias Mader[1,2], Louis Costa[1,2], Christian Deutsch[1,2], Jakob Reichel[3], Theodor W. Hänsch[1,2], and David Hunger[1,2]

1. Ludwig-Maximilians Universität München, Germany
2. Max-Planck-Institut für Quantenoptik, Garching, Germany
3. Laboratoire Kastler Brossel, CNRS, E.N.S., Paris, France
**hanno.kaupp@physik.uni-muenchen.de*

Optical fibers with machined and coated end facets can serve as high reflectivity mirrors to build low loss optical resonators with free space access [1, 2]. These microcavities feature a very small mode volume on the order of a few tens of cubic wavelengths and a very large Finesse of up to 105, corresponding to quality factors of several millions. Thus, the Purcell factor being proportional to the ratio of quality factor and mode volume can be as high as 104, which can dramatically increase the emission rate of an emitter inside the cavity.

We use the microcavities to couple solid state based emitters such as color centers in diamond to the cavity. First results from spectra of ensembles of nitrogen-vacancy centers coupled to the cavity show a strongly increased emission efficiency into the cavity mode. The emission behavior can be modeled with a modified Purcell factor accounting for the dephasing.

References
[1] D. Hunger, New Journal of Physics **12**, 065038 (2010).
[2] D. Hunger, AIP Advances **2**, 012119 (2012).

Size effects on thermal radiation of a dielectric microparticle

Maki Tachikawa, Hitoshi Odashima, Naoya Kase, and Kousuke Nagase

Department of Physics, Meiji Universiry, Kawasaki City, Kanagawa, Japan
**tachikaw@isc.meiji.ac.jp*

Although Planck's law of blackbody radiation well describes spectral profiles of thermal radiation from macroscopic objects, it remains an open question if Planck's formula applies to particles of size comparable to optical wavelengths. We experimentally demonstrate that thermal radiation from a micron-sized dielectric particle depends sensitively on its morphology and optical properties. Our laser trapping technique levitates a high-temperature microsphere of aluminum oxide and enables emission spectroscopy of the single particle [1]. As the particle becomes smaller, a blackbody-like spectrum turns into a spectrum dominated by multiple peaks resonant with whispering gallery modes of the spherical resonator. Analysis of the particle size dependence of the emission power reveals that the emissivity of a microparticle strongly depends on the extinction coefficient and the liquid-solid phase transition occurred in the optical trap.

Reference

[1] H. Odashima, M. Tachikawa, and K. Takehiro, "Mode-selective thermal radiation from a microparticle", Phys. Rev. A **80**, 041806(R) (2009).

Coherently pumped cavity-QED microlaser

Junki Kim, Younghoon Song, and Kyungwon An*

Department of Physics & Astronomy, SNU, Seoul, Korea
**kwan@phya.snu.ac.kr*

The cavity-QED micromaser/laser is the maser/laser system based on coherent interaction between a small number of two-level atoms and a high finesse cavity field. So far incoherently pumped micromaser/lasers have been experimentally realized and studied. For the micromaser/laser coherently pumped by injecting atoms in a coherent superposition state, there are many interesting predictions such as symmetry breaking in the cavity field and generation of a mesoscopic cat state yet to be confirmed. Here, we present our experimental progress toward realization of the coherently pumped microlaser. In our experiment both atomic position control and superposition state pumping are made possible by employing an atomic beam aperture with an array of nanoholes with a period matching the resonance wavelength(791 nm of barium ${}^1S_0$-${}^3P_1$ transition). The cavity mirrors are specially shaped so that the nanohole aperture can be brought to the cavity mode within 300 μm for preventing atomic position spread. Preliminary data on coherent pumping will be presented and discussed.

Reference

[1] Krause, J. and Scully, M. O. and Walther, H "Quantum theory of the micromaser-Symmetry breaking via off-diagonal atomic injection", Phys, Rev. A **34**, 2032-2037 (1986).

Quantum correlated pulses from a synchronously pumped optical parametric oscillator

V. A. Averchenko[1,*], K. Hammerer[1], C. Fabre[2], N. Treps[2], and Yu. M. Golubev[3]

1. Institute for Theoretical Physics and Institute for Gravitational Physics, Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany
2. Laboratoire Kastler Brossel, Universite Pierre et Marie Curie - Paris 6, ENS, CNRS; 4 place Jussieu, 75252 Paris, France
3. St. Petersburg State University, ul. Ul'yanovskaya, 1, Stary Petershof, 198504 St. Petersburg, Russia
**valentin.averchenko@aei.mpg.de*

Optical frequency comb with non-classical properties can be produced via parametric down-conversion of a pumping comb in a degenerate synchronously pumped optical parametric oscillator. In the time domain we developed a quantum theory of the oscillator that describes its operation both below and above oscillation threshold and gives clear insight into the character of quantum properties of an output signal comb being a train of pulses. Now we are thinking about application of a frequency comb and its non-classical counterpart for ultra-precise position sensing, particularly, in gravitational wave detectors. Here the fundamental limit on an accuracy of position determination (standard quantum limit) appears as interplay between time-arrival uncertainty of pulses and light back-action on a mechanical sub-system.

Tu-144 Quantum simulators…

Direct observation of coherent backscattering of ultracold atoms

Kilian Müller[1], Fred Jendrzejewski[1], Jérémie Richard[1], Alain Aspect[1], Philippe Bouyer[2], and Vincent Josse[1,*]

1. Laboratoire Charles Fabry, Unité Mixte de Recherche 8501, Institut d'Optique Centre National de la Recherche Scientifique, Université Paris-Sud, Palaiseau, France
2. Laboratoire Photonique, Numérique et Nanosciences, Unité Mixte de Recherche 5298 Université Bordeaux, Institut d'Optique and Centre National de la Recherche Scientifique, Talence, France
**vincent.josse@institutoptique.fr*

Phase coherence has dramatic effects on the transport properties of waves in random media. Interferences between certain scattering events may act against diffusion, and eventually lead to a complete halt of the wave (Anderson localization). In momentum space, such interference effects manifest themselves as the well-known coherent back scattering (CBS) peak, i.e. an enhanced scattering in the backward direction. A remarkable tool to probe phase coherence in mesoscopic systems, CBS has been widely studiedwith various kinds of waves, from light to electronic waves [1]. Here we report the direct observation of CBS of ultracold atoms in presence of disorder. Following the landmark experiments that have demonstrated Anderson localization, it constitutes a smoking gun of phase coherence in ultracold disordered gases. This opens new prospects to investigate phase coherence properties, and especially the emergence of Anderson transition in 3D.

Reference

[1] E. Akkermans and G. Montambaux, *Mesoscopic Physics of Electrons and Photons*, Cambridge University Press, London, 2007).

Towards single-atom-resolved detection and manipulation of strongly correlated fermions in an optical lattice

Graham D. Bruce*, Andrew Kelly, James Hudson, Andreas Schindewolf,
Elmar Haller, and Stefan Kuhr

Department of Physics, University of Strathclyde, SUPA, Glasgow G4 0NG, UK
**graham.bruce@strath.ac.uk*

Motivated by the recent achievement of single-site-resolved imaging and manipulation of strongly correlated bosonic systems in an optical lattice, we illustrate our progress and future plans in our attempts to realize a fermionic quantum simulator. Detecting and manipulating strongly correlated fermionic systems at the level of a single atom will further exploit the potential of ultracold atoms as a quantum simulator for, e.g., the Fermi-Hubbard model, which is a key model in condensed matter physics.

Atoms from a two-stage magneto-optical trap of ^{87}Rb and ^{40}K are loaded into a magnetic trap, before evaporative cooling and transport in an optical trap delivers a quantum degenerate gas to a 3-dimensional optical lattice. By selective removal of atoms from all lattice planes but the one at the focal plane of a NA = 0.68 microscope objective, we will resolve the distribution and evolution of atoms across individual sites of the 2D lattice using fluorescence imaging. We plan to use this novel detection method to characterize, e.g., temperature, spin-structure, or entropy distribution of quantum phases such as fermionic Mott insulators, Band insulators, metallic phases or Néel antiferromagnets. Single-site manipulation will be possible by means of an addressing beam focused by the imaging microscope, which will allow us to investigate the effect of local perturbations on the system.

Collective oscillation of a Spin-Orbit coupled Bose-Einstein condensate

Jin-Yi Zhang[1], Si-Cong Ji[1], Long Zhang[1], Zhu Chen[2], Zhi-Dong Du[1],
You-Jin Deng[1], Hui Zhai[2], Shuai Chen[1,*], and Jian-Wei Pan[1,*]

1. Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230027, China
2. Institute for Advanced Study, Tsinghua University, Beijing, 100084, China
**shuai@ustc.edu.cn, pan@ustc.edu.cn*

We experimentally produce a Spin-Orbit coupled Bose-Einstein condensate with the technique of Raman coupling and systematically study the dynamical properties of such a condensate. We present an experimental study of the collective dipole oscillation of a spin-orbit (SO) coupled Bose-Einstein condensate in a harmonic trap. A number of interesting properties is observed. The frequency of the center-of-mass dipole oscillation deviatesfrom the harmonic trap frequency and depends on the oscillation amplitude, as a manifestation of the change of single-particle dispersion. A magnetization oscillation induced by the dipole oscillation is also observed, revealing the coupling of the spin to the momentum of an atom and the absence of Galilean invariance of this system. These experimental results are then compared to theoretical calculations based on variational wave function approximation.

Reference

[1] Shuai Chen et.al., *Revealing Unconventional Properties of a Spin-Orbit Coupled Bose-Einstein Condensate from Collective Dipole Oscillation*, arXiv: 1201.6018.

Simulation of electric dipole moment of neutral relativistic particles

T. G. Tenev*, Peter A. Ivanov, and Nikolay V. Vitanov

Department of Physics, Sofia University, 5 James Bourchier Blvd., Sofia 1164, BG
**tenev@phys.uni-sofia.bg*

The electric dipole moments of various neutral elementary particles, such as neutron, neutrinos, certain hypothetical dark matter particles and others, are predicted to exist by the standard model of high energy physics and various extensions of it. However, the predicted values are beyond the present experimental capabilities. We propose to simulate and emulate the electric dipole moment of neutral relativistic particles and the ensuing effects in the presence of electrostatic field by simulation of an extended Dirac equation in ion traps.

Strongly correlated bosons on frustrated optical lattices

Tommaso Roscilde

Laboratoire de Physique, Ecole Normale Supérieure de Lyon, 46 Allée d'Italie, 69007 Lyon, France

Artificial gauge fields open the route to the realization of unconventional bosonic phases in optical lattices, including condensate phases in which the bosons create an array of persistent currents whose "handedness" (chirality) corresponds to an emergent, discrete degree of freedom; and novel bosonic insulators, which are the particle analog of exotic spin liquid phases for quantum spins, among others. Here we will present a variety of theoretical results concerning strongly interacting bosons on a frustrated lattice, as recently realized in a seminal experiment [1]. We will address the separation between the onset of condensation and of chiral order (detected in time-of-flight measurements by the unequal height of the diffraction peaks), and the possibility of measuring it for the first time in experiments on frustrated triangular and square lattices; moreover we will illustrate the possibility of observing spin liquid phases for the same lattice geometries in the limit of half filling.

Reference

[1] J. Struck *et al.*, Science **333**, 996 (2011).

Observation of phonon hopping in radial vibrational modes of trapped ions

Shinsuke Haze[1,*], Atsushi Noguchi[2], Kenji Toyoda[2], and Shinji Urabe[2]

1. Institute for Laser Science, University of Electro-Communications, Tokyo, Japan
2. Grad. School of Engineering Science, Osaka University, Osaka, Japan
**haze@ils.uec.ac.jp*

Trapped and laser cooled ions are the promising candidates for realizations of quantum information processors and simulators. Recently, many experiments related to quantum simulation with trapped ions are reported and quantum phase transition of Ising spin model are observed.

Our goal is to simulate Bose-Hubbard model (BHM) by using ions. The radial vibrational phonons act as bosons in BHM and the coulomb coupling between ions induces phonon hopping [1]. Here we report observation of phonon hopping dynamics of two trapped $^{40}Ca^{+}$ and the measured hopping rate is a few kHz [2]. Moreover, we succeeded in controlling the hopping rates by changing the inter-ion distance and this work is the essential step for physical implementation of BHM simulator with trapped ions.

References
[1] D. Porras and J. I. Cirac, Phys. Rev. Lett. **93**, 263602 (2004).
[2] S. Haze, Y. Tateishi, A. Noguchi, K. Toyoda, and S. Urabe, Phys. Rev. A, **85**, 031401(R) (2012).

Relativistic and multipole effects on the polarization of Lyman line emission following radiative recombination of bare ions

M. K. Inal* and L. Bettadj

Département de Physique, Université A. Belkaid, 13000 Tlemcen, Algeria
**m_inal@mail.univ-tlemcen.dz*

We calculated the polarization degree of the Ly-α_1 and Ly-β_1 lines emitted by highly charged H-like ions after radiative recombination (RR) of bare nuclei with unidirectional electrons. These calculations were performed for several ions with atomic numbers $10 \leq Z \leq 92$ and various incident electron kinetic energies from 0.01 to 10 times the 1*s* ionization potential, and have included RR into states with principal quantum number up to n=6 followed by cascades. Three sets of the RR cross sections to magnetic sublevels were computed: the first two in the electric-dipole approximation with the non-relativistic and relativistic electron wavefunctions and the third in the exact relativistic method including all multipoles of the radiation field [1]. The results of our polarization calculations using these three sets of cross-section data were compared with each other in order to reveal the importance of the relativistic and multipole effects as Z and the electron energy increase.

Reference
[1] L. Bettadj, M. K. Inal, A. Surzhykov and S. Fritzsche, ‘‘Effects of the radiative recombination on the intensity and polarization of the Ly-a emission of hydrogen-like ions’’, Nucl. Instr. Meth. B **268**, pp. 3509-3516 (2010).

Inelastic collisions of Al and Sb atoms with helium in homogeneous magnetic fields

Eunmi Chae[1,3], Colin B. Connolly[1,3,*], Yat Shan Au[1,3], Timur V. Tscherbul[3,4], Alexei A. Buchachenko[5], Hsin-I. Lu[3,6], Wolfgang Ketterle[2,3], and John M. Doyle[1,3]

1. Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
2. Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
3. Harvard-MIT Center for Ultracold Atoms, Cambridge, Massachusetts 02138, USA
4. ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
5. Laboratory of Molecular Structure and Quantum Mechanics, Department of Chemistry, Moscow State University, 119899 Moscow, Russia
6. School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
**colin@cua.harvard.edu*

We present an experimental and theoretical study of Al and Sb colliding with helium at 800 mK. Zeeman relaxation in atom–He collisions can serve as a probe of their interaction potentials. We observe Zeeman relaxation by measuring dynamics of the magnetic sublevel distribution in different Zeeman states in homogeneous magnetic fields. Both Al and Sb show rather rapid relaxation; however, the relaxation mechanisms are different. In the case of Al, the anisotropic $^2P_{3/2}$ excited state is mixed with the isotropic $^2P_{1/2}$ ground state during a collision to cause relaxation. We investigate both m_J- and J-changing collisions as a function of magnetic field to further confirm the theoretical model previously developed for In and Ga. In the case of Sb, spin-orbit coupling mixes $L \neq 0$ states into the ground state($^4S_{3/2}$), and hence introduces electronic anisotropy into its interaction with He. This work constrains the Sb-He potentials and extends our understanding of cold collisions in pnictogens.

Dielectronic Recombination rates for Ar^{6+} and Kr^{24+}

Alaa Abo-Zalam[1], Abdel-Aziz Habeeb[1], and Hassan Ramadan[2,*]

1. Physics Department, Faculty of Science, Menofia University, Menofia, Egypt
2. Basic Sciences, Dept., Faculty of Computer and Information Sciences, Ain Shams University, Cairo, Egypt
**contact.hassram2000@yahoo.com*

In thermal plasma, the ion- atom collisions proceed most probably though resonance processes. One of the important processes is resonate transfer excitation (RTE) followed by emission X-ray (RTEX). It causes a self cooling for plasma. In addition, it is identical to the dielectronic recombination (DR) in electron-ion collisions. The present wok deals with the calculation of DR rate coefficients (α^{DR}′s) and DR cross sections (σ^{DR}′s) as well as RTEX cross sections (σ^{RTEX}′s) for Mg-like ions [Ar^{6+} and K^{24+}] with L- shell and K-shell excitation for $\Delta n = 0$ and $\Delta n \neq 0$. Specifically, RTEX cross sections are calculated for the collusion of Ar^{6+} and Kr^{24+} ions with He and H_2 targets. The calculations are carried out using the adapted angular momentum average (AMA) scheme in the isolated resonance approximation (IRA). The results are compared with other results [1] for the same ions.

Reference

[1] Takeshi Kai, Rajesh Srivastave, and Shinobu Nakazaki, Phys. Rev. **A 70**, pp. 062705 (2004).

Macroscopic quantum self-trapping in dynamical tunnelling

S. Wüster,[1,2,*], B. J. Dąbrowska[1], and M. J. Davis[1]

1. The University of Queensland, School of Mathematics and Physics, Brisbane, Qld 4072, Australia
2. Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Strasse 38, 01187 Dresden, Germany
**sew654@pks.mpg.de*

It is well-known that increasing the nonlinearity due to repulsive atomic interactions in a double-well Bose-Einstein condensate suppresses quantum tunnelling between the two sites. Here we find analogous behaviour in the dynamical tunnelling of a Bose-Einstein condensate between period-one resonances in a single driven potential well.

For small nonlinearities we find unhindered tunnelling between the resonances, but with an increasing period as compared to the non-interacting system. For nonlinearities above a critical value we generally observe that the tunnelling shuts down. However,for certain regimes of modulation parameters we find that dynamical tunnelling re-emerges for large enough nonlinearities, an effect not present in spatial double-well tunnelling. We develop a two-mode model in good agreement with full numerical simulations over a wide range of parameters, which allows the suppression of tunnelling to be attributed to macroscopic quantum self-trapping.

Reference

[1] S. Wüster, B. J. Dąbrowska and M. J. Davis, *Macroscopic Quantum Self-Trapping in Dynamical Tunnelling*, http://arxiv.org/abs/1112.2086.

Long-range Rydberg-Rydberg interactions in two-electron atoms

C. L. Vaillant*, M. P. A. Jones, and R. M. Potvliege

Durham University, Department of Physics, South Road, Durham, DH1 3LE, UK
**c.l.j.j.vaillant@durham.ac.uk*

We present perturbative calculations of dipole-dipole and quadrupole-quadrupole long-range interactions between calcium, strontium and ytterbium Rydberg atoms based on the Coulomb approximation and degenerate perturbation theory. Expressions are given forthe leading order dispersion coefficients, C_5 (first-order quadrupole-quadrupole) and C_6 (second-order dipole-dipole), in terms of radial matrix elements and angular factors [1,2].

The Coulomb approximation enables the use of analytic expressions for the radial matrix elements [3] requiring only the orbital angular momentum and binding energies of the electronic states. The latter are obtained by extrapolation from quantum defect fits to experimental data.

Examination of the results reveals large variations between the different series. Two Förster resonances are found in the range examined, both in triplet states of strontium. Particular attention is paid to the isotropic *S* states of strontium and ytterbium, where attractive interactions are found for strontium and comparatively weak repulsive interactions in ytterbium.

References

[1] Vaillant C. L., Jones M. P. A. and Potvliege R. M. 2012, arXiv:1203.3736.
[2] Singer K., Stanojevic J., Weidemüller M. and Côté R. 2005 *J. Phys.* B **38** S295.
[3] Oumarou B., Picart J., Tran Minh N. and Chapelle J. 1988 *Phys. Rev.* A **37**, 1885.

Towards photon blockade using Rydberg superatoms

D. Maxwell*, H. Busche, D. Paredes, D. Szwer, M. P. A. Jones, and C. S. Adams

Department of Physics, Durham University, Durham, UK
**daniel.maxwell@durham.ac.uk*

Rydberg blockade limits the number of excitations in an atomic ensemble to one, creating a powerful platform for quantum information processing using neutral atoms [1]. It is possible to map the Rydberg blockade process into a photon blockade, producing a large optical non-linearity [2]. In our experiments we aim to isolate a single blockaded ensemble, or superatom, and exploit the photon blockade process to produce non-classical states of light. We tightly confine an ultra-cold cloud of rubidium atoms in a strongly focused dipole trap. Electromagnetically induced transparency is used to map the non-linear response of the medium onto the probe laser field.

In recent experiments we have focused on the writing and reading of Rydberg polaritons in the ensemble providing information on the dephasing of the superatom.

References

[1] M. D. Lukin *et al.*, *Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles*, Phys. Rev. Lett. **87**, 037901 (2001).
[2] J. D. Pritchard *et al.*, *Cooperative Atom-Light Interaction in a Blockaded Rydberg Ensemble*, Phys. Rev. Lett. **105**, 193603 (2010).

Non-gaussian distribution of photoassociated cold atom

Jun-Ren Chen, Cheng-Yang Kao, and Yi-Wei Liu*

Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
**ywliu@phys.nthu.edu.tw*

The momentum distribution of cold atom with photoassociation was studied using laser -cooled and trapped ^{85}Rb. Due to the energy conservation, a pair of atoms can only be associated, if its internal kinetic energy is equal to the detuning of the excitation laser. In our photoassociation trap loss experiment, the atoms with a certain velocity was "kicked" out of trap by controlling the laser frequency. The momentum distribution was then manipulated and observed using time-of-flight. A non-gaussianvelocity distribution was resulted.

High resolution spectroscopy of interacting Rydberg gases

Robert Löw*, Johannes Nipper, Jonathan Balewski, Alexander Krupp, and Tilman Pfau

Physikalisches Intitut, Universität Stuttgart, Germany
**r.loew@physik.uni-stuttgart.de*

The giant size and large polarizibility of Rydberg-atoms, resulting in strong long-range Rydberg-Rydberg interactions, make them ideal to study many-body effects in ultracold atomic gases. We use an interferometric technique based on an optical Ramsey sequence to study such resonances in the $44d_{5/2}$ Rydberg state of ultracold ^{87}Rb atoms. With this phase sensitive method we show that we can switch and tune the inter-atomic interaction [1]. Extending the scheme using different electric pulse sequences we can additionally probe the coherent coupling of the involved pair states [2]. The coherent nature of the Förster induced interaction is crucial for many of its applications. Furthermore the system presented here could be used to model Förster induced energy transfer processes which play an important role in biophysics.

References

[1] J. Nipper, J. B. Balewski, A. T. Krupp, B. Butscher, R. Löw, and T. Pfau, “Highly Resolved Measurements of Stark-Tuned Förster Resonances between Rydberg Atoms”, Phys. Rev. Lett. **108** 113001 (2012).
[2] J. Nipper, J. B. Balewski, A. T. Krupp, S. Hofferberth, R. Löw, T. Pfau, “Förster interaction induced phase shift in a pair state interferometer”, accepted in Phys. Rev. X, arXiv:1203.1851.

Intensity correlations in electromagnetically induced absorption

Hee Jung Lee, Sang Min Lee, and Han Seb Moon*

Department of Physics, Pusan National University, Busan 609-735, Korea
**hsmoon@pusan.ac.kr*

Recently, the intensity-intensity correlations between probe and coupling lasers in electromagnetically induced transparency (EIT) have been reported [1, 2]. However, we first observed intensity correlations between the coupling and probe lasers interacted with Rb atoms under condition of electromagnetically induced absorption (EIA). The intensity correlations between two counter-circular polarized coupling and probe laser in the Hanle configuration were investigated as a function of the applied magnetic field. When the condition of EIA medium was changed from on-resonance to off-resonance as a function of the magnetic field strength, the second order correlation function $G^{(2)}(0)$ was transformed from 0.3 (correlation) to -0.9 (anti-correlation). Also, $G^{(2)}(0)$ of EIA medium was measured as functions of the incident laser power and the temperature of the Rb atomic vapor cell. We could illuminate the intensity correlation and anti-correlations of EIA using the N-type four-level atomic model.

References

[1] V. A. Sautenkov, Y. V. Rostovtsev, and M. O. Scully, “Switching between photon-photon correlations and Raman anticorrelations in a coherently prepared Rb vapor”, Phys. Rev. A **72**, 065801 (2005).
[2] G. O. Ariunbold, Y. V. Rostovtsev, V. A. Sautenkov, and M. O. Scully “ Intensity correlation and anti-correlations in coherently driven atom vapor,” J. Mod. Opt. **57**, 1417-1427 (2010).

Avalanche ionization dynamics of a strongly blockaded Rydberg gas

Martin Robert-de-Saint-Vincent*, Christoph S. Hofmann, Hanna Schempp,
Georg Günter, Shannon Whitlock, and Matthias Weidemüller

Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany
**robertdesaintvincent@physi.uni-heidelberg.de*

The production of strongly coupled plasmas, where the Coulomb interaction between neighbouring particles dominates their kinetic energy, would allow for better understanding of dense astrophysical plasmas and for preparing bright, correlated ion and electron sources [1]. The strongly coupled regime is however hardly reached so far by ionising ultra-cold atomic or molecular gases, due in part to a fast re-equilibration of the ion spatial distribution. This phenomenon, called disorder-inducedheating, could be prevented by starting from a pre-organised sample [2]. To do so, we release a dense ^{87}Rb cloud from an optical dipole trap, and continuously couple the atoms to the $|55S\rangle$ Rydberg state. Using combined opticaland ion detection, we observe a sudden ionisation avalanche, triggered despite repulsive Rydberg interactions. Prior to its onset, we observe that strong spatial correlations have already built up between Rydberg atoms, which should be preserved in the avalanche to form a strongly correlated plasma.

References

[1] T. C. Killian, T. Pattard, T. Pohl, and J. M. Rost, *Ultracold Neutral Plasmas*, Phys. Rep. **449**, pp. 77-130 (2007).

[2] M. S. Murillo, *Using Fermi Statistics to Create Strongly Coupled Ion Plasmas in Atom Traps*, Phys. Rev. Lett. **87**, pp. 115003 (2001).

Impact of collisions with neutral Hydrogen on spectral lines' polarization of a multilevel atomic model

Kebaier Kaouther[1,*], Jaidane Nejmeddine[1], and Derouich Moncef[1,2]

1. Laboratoire de spectroscopie Atomique Moléculaire et Applications, Faculté des sciences de Tunis, Tunisie
2. Institut d'Astrophysique Spatiale (IAS) bat 121 - Université Paris Sud 91405 Orsay Cedex, France
**derouichmoncef@gmail.com*

In order to interpret the spectrum of the linear polarization which is produced by scattering processes observed close to the solar limb, we need to evaluate the impact of collisions with neutral Hydrogen atoms on polarization's signals of some neutral and ionized atoms.

We present preliminary results concerning the calculation of emergent fractional linear polarization amplitudes produced by scattering processes by radiation field, these calculations involve collisional rate calculations.

Vortices in the final-state continuum of a positron-atom ionization collision

V. D. Rodríguez[1,*], F. Navarrete[2], R. Della Picca[2], J. Fiol[2], and R. O. Barrachina[2]

1. Departamento de Física and Instituto de Física de Buenos Aires, FCEyN, Universidad de Buenos Aires, 1428 Buenos Aires Argentina
2. Centro Atómico Bariloche and Instituto Balseiro (Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo), 8400 S. C. de Bariloche, Río Negro, Argentina
**vladimir@df.uba.ar*

We employ a continuum distorted wave (CDW) approximation with the correct kinematics to calculate the probability flux of the final-state continuum in the ionization of atoms by positron impact. Different structures are unveiled and investigated, among them a vortex, akin to a deep minimum recently uncovered in the triple differential cross section for electron-atom ionization collision [1]. We also explore how this structure develops in the multidimensional continuum of the impinging positron, the emitted electron and the recoiling ion. Finally, we discuss this finding in the framework of Madelung's hydrodinamical and de Broglie - Bohm formulations of Quantum Mechanics.

Reference

[1] J. H. Macek, J. B. Sternberg, S. Y. Ovchinnikov and J. S. Briggs, "Theory of Deep Minima in (e,2e) Measurements of Triply Differential Cross Sections", Phys. Rev. Lett. **104**, 033201 (2010).

Feshbach resonances in cesium at ultra-low static magnetic fields

D. J. Papoular[1,2,*], S. Bize[3], A. Clairon[3], H. Marion[3], S. J. Kokkelmans[4], and G. V. Shlyapnikov[2,5]

1. INO-BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Povo, Italy
2. LPTMS, CNRS, Université Paris-Sud, F-91405, Orsay, France
3. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, F-75014 Paris, France
4. Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
5. Van der Waals–Zeeman Institute, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
**papoular@science.unitn.it*

We have observed Feshbach resonances for ^{133}Cs atoms in two different hyperfine states at ultra–low static magnetic fields by using an atomic fountain clock. The extreme sensitivity of our setup allows for high signal–to–noise–ratio observations at densities of only 2×10^7 cm^{-3}. We have reproduced these resonances using coupled–channels calculations which are in excellent agreement with our measurements. We justify that these are S–wave resonances involving weakly–bound states of the triplet molecular Hamiltonian, identify the resonant closed channels, and explain the observed multi–peak structure. We also describe a model which precisely accounts for the collisional processes in the fountain and which explains the asymmetric shape of the observed Feshbach resonances in the regime where the kinetic energy dominates over the coupling strength.

Reference

[1] D. J. Papoular, S. Bize, A. Clairon, H. Marion, S. J. Kokkelmans, and G. V. Shlyapnikov, *Feshbach Resonances in Cesium at Ultra–Low Static Magnetic Fields*, arXiv:1205.2553.

Studying two-photon cooperative absorption on cold atoms

Edwin Pedrozo-Peñafiel, Rafael R. Paiva, Franklin J. Vivanco, Vanderlei S. Bagnato, and Kilvia M. Farias*

Instituto de Física de São Carlos, Universidade de São Paulo - SP, Brasil
**kilvia@ifsc.usp.br*

The phenomenon of two-photon cooperative absorption is common in solid-state physics [1]. In a sample of trapped cold atoms, that effect may open up new possibilities for the study of nonlinear effects. In this work, we demonstrate the occurrence of a two-photon cooperative absorption in a pair of colliding cold Na atoms kept in a magneto-optical trap. In our experiment, we start with two colliding Na atoms in the S hyperfine ground state. The pair absorbs two photons, resulting in: a $P_{1/2}$ and a $P_{3/2}$ atom. The result of this excitation is observed by ionization using an external light source. A model that considers only dipole-dipole interactions between the atoms allows us to understand the basic features observed in the experimental results. Both the pair of generated atoms and the photons originating from their decay are correlated and may have interesting applications that remain to be explored.

Reference

[1] J. R. Rios Leite *et al.*, Chem. Phys. Lett. 73, 71 (1980).

Ultracold polar molecule collisions in quasi-1D geometries

A. Simoni[1,*], J.-M. Launay[1], Z. Idziaszek[2], and P. S. Julienne[3]

1. Institut de Physique de Rennes, UMR 6251 CNRS-Université de Rennes 1
35042 Rennes Cedex, France
2. Faculty of Physics, University of Warsaw, 00-681 Warsaw, Poland
3. Joint Quantum Institute, NIST and the University of Maryland, Gaithersburg
Maryland 20899-8423, USA
**andrea.simoni@univ-rennes1.fr*

We study collisions of polar molecules confined in quasi-1D optical lattices. Molecules are treated as fixed dipoles and the short-range dynamics is modeled by the complex boundary condition introduced in [1]. We solve the scattering equations using a spectral element discretization approach that ideally exploits the sparse nature of the potential coupling matrix and guarantees high accuracy. Elastic, inelastic, and reactive rates are calculated as a function of the applied electric field and collision energy. When the field is perpendicular to the trap axial direction, depending on the experimental parameters the reaction rates can be strongly suppressed, stabilizing the gas versus reactive processes. The difference between bosonic and fermionic symmetry cases is discussed. The numerical results are interpreted on the basis of simple energy barrier considerations and of reduced adiabatic models.

Reference

[1] Z. Idziaszek and P. S. Julienne, *Universal Rate Constants for Reactive Collisions of Ultracold Molecules*, Phys. Rev. Lett. **104**, 113202-1-4 (2010).

Geometric phase in electron exchange excitation of a single atom

J. F. Williams*, L. Pravica, S. N. Samarin, K. Sudarshan, and P. Guagliardo

Centre for Atomic, Molecular, Surface Physics; ARC Centre for Antimatter-Matter Studies, School of Physics, University of Western Australia, Perth, 6009 Australia
**jfw@physics.uwa.edu.au*

A geometrical (Berry) phase of 180^o has been observed in the electron spin exchange excitation of zinc atoms from the ground $(3d^{10}4s^2)^1S_0$ state (M_S=0) to the $(3d^{10}4s5s)^3S_1$ (M_S=0) state. The Stokes parameter P_2 (aligned linear polarization) of the light emitted in the optical 468.1, 472.3, and 481.1 nm decays to the $(3d^{10}4s4p)^3P_{0,1,2}$ states reveals an aligned angular momentum. The excitation from a ^1S to a ^3S state was expected to be a pure exchange process but the Fermi statistics and Pauli exclusion principle establish the phase change of 180^o. The Pauli sign is a geometric phase factor of topological origin such that the electron spin is "parallel transported" around a closed path and acquires a fixed phase which is not changed by the kinematics of the excitation exchange process.

Reference
[1] J. F. Williams, L. Pravica, and S. N. Samarin, "Topological angular momentum in electron exchange excitation of a single atom." Phys Rev A 85 022701 (1012).

Controlling chemical reactions of a single particle

Carlo SIas*, Lothar Ratschbacher, Cristoph Zipkes, and Michael Köhl

Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
**cs540@cam.ac.uk*

The full control over all quantum mechanical degrees of freedom in binary collisions allows for the identification of fundamental interaction processes and for steering chemical reactions. Focussing on the best-controlled experimental conditions, such as using state-selected single particles and low temperatures, is crucial for the investigation of chemical processes at the most elementary level.

The hybrid system of trapped atoms and ions offers key advantages in this undertaking: ion traps have a large potential well depth in order to trap the reaction products, while the absence of a Coulomb-barrier allows the particles to collide at short internuclear distance.

Here, we report on the experimental tuning of the exchange reaction rates of a single trapped ion with ultracold neutral atoms by exerting control over both their quantum states. We observe the influence of the hyperfine state on chemical reaction rates and branching ratios and monitor the kinematics of the reaction products. These investigations advance chemistry with single trapped particles towards achieving quantum-limited control of chemical reactions and pave the way to the study of the coherence properties of a single trapped ion in an ultracold buffer gas.

Elastic scattering of positronium using the confined variational method

Jun-Yi Zhang[1], Ying Qian[2], Zong-Chao Yan[3,4], and Udo Schwingenschlögl[1]

1. Division of Physical Science & Engineering, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
2. Supercomputing Laboratory, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
3. Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
4. Department of Physics, University of New Brunswick, Fredericton E3B 5A3, Canada
**Junyi.Zhang@kaust.edu.sa*

We demonstrate that the phase shift in elastic S-wave positronium (Ps)-atom scattering can be precisely determined by the confined variational method, in spite of the fact that the Hamiltonian includes an unphysical confining potential acting on the center-of-mass of the positron and one of the atomic electrons. The calculated phase shifts are precise mainly because the unphysical effect of the potential can be eliminated by adjusting the confining potential. Using the stochastic variational method, explicitly correlated Guassian-type basis functions are optimized and the energies of confined Ps-atom systems are determined. Then the discrete energies are taken as a reference for tuning auxiliary one-dimensional potentials. The phase shifts calculated for the one-dimensional potential scattering are the same as the phase shifts of the Ps-atom scattering. For the Ps-hydrogen scattering, the present calculations are in very good agreement with the Kohn variational calculations. Therefore, the 2% ~ 4% discrepancy between the Kohn variational and R-matrix calculations is resolved. For Ps-helium scattering, our calculations achieve a higher precision than reported in any previous publication.

A high-flux polar molecular radical source for the ThO eEDM experiment

Elizabeth Petrik[1,*], Paul Hess[1], Börge Hemmerling[1], Nicholas Hutzler[1], Emil Kirilov[2], Ivan Kozyryev[1], Benjamin Spaun[1], Amar Vutha[3], David DeMille[2], Gerald Gabrielse[1], and John Doyle[1]

1. Harvard University, Cambridge, Massachusetts, USA
2. Yale University, New Haven, Connecticut, USA
3. York University, Toronto, Ontario, Canada
**epetrik@physics.harvard.edu*

A bright, stable beam of cold thorium monoxide is an essential component of an ongoing experiment to measure the electron's electric dipole moment [1]. The source presents interesting technical challenges since ThO is reactive, while its production precursors, thorium metal and thorium dioxide, are highly refractory. We have realized a ThO source that produces 10^{13} molecules sr^{-1} s^{-1} in a single ro-vibrational level [2]. A ThO_2 ceramic in a cryogenic buffergas cell is laser ablated to produce pulses of gas-phase ThO, which is cooled by the buffer gas before exiting the cell in a beam. We are also developing a continuous source of ThO via a high-temperature reaction between Th and ThO_2 that promises increased peak and time-averaged yields. We discuss ongoing work and recent results.

References

[1] A. C. Vutha *et al.*, *Search for the electric dipole moment of the electron with thorium monoxide*, J. Phys. B **43**, p. 074007 (2010).
[2] N. R. Hutzler *et al.*, *A cryogenic beam of refractory, chemically reactive molecules with expansion cooling*, Phys. Chem. Chem. Phys. **13**, pp. 18976-18985 (2011).

Towards a quantum gas of polar YbCs molecules

R. Freytag*,[1], K. L. Butler[2], M. Petersen[1], S. A. Hopkins[2], D. A. Brue[2], J. M. Hutson[2], E. A. Hinds[1], S. L. Cornish[2], and M. Tarbutt[1]

1. The Blackett Laboratory, Imperial College London, London, UK
2. Department of Physics, Durham University, Durham, UK
**rf207@ic.ac.uk*

The potentials of ultracold polar molecules have been discussed with respect to quantum information processing and quantum simulation [1]. This experiment focuses on the production of quantum degenerate YbCs molecules. We propose to magneto-associate the atoms over a Feshbach resonance [2] and transfer them to the ground state using Stimulated Raman Adiabatic Passage (STIRAP) [3]. Ground state YbCs will, due to its singe valence electron, exhibit an electric as well as a magnetic dipole moment. It should therefore exhibit spin dependent interactions in addition to long-range dipole-dipole interactions [1]. Here we outline the theoretical and experimental progress on creating a dual species Magneto-Optical Trap (MOT) of Yb and Cs.

References
[1] A. Micheli, G. K. Brennen and P. Zoller, “A toolbox for lattice-spin models with polar molecules”, Nature Physics **2**, pp. 341-347 (2006).
[2] T. Köhler, K. Goral, P. S. Julienne, “Production of cold molecules via magnetically tunable Feshbach resonances”, Rev. Mod. Phys. **78**, pp. 1311-1361 (2006).
[3] K. Bergmann, H. Theuer and B. W. Shore, “Coherent population transfer among quantum states of atoms and molecules”, Rev. Mod. Phys. **70**, pp. 1003-1025 (1998).

Making a magneto-optical trap for polar molecules

Matthew T. Hummon[1], Mark Yeo[1], Benjamin K. Stuhl[1], Alejandra Collopy[1], Yong Xia[2], and Jun Ye[1]

1. JILA, NIST and University of Colorado, 440 UCB, Boulder, CO 80309, USA
2. East China Normal University, Shanghai, China

The development of laser cooling and trapping for a diverse set of atomic species revolutionized atomic and quantum physics. Expanding the techniques of laser cooling and trapping to molecules would provide new systems with complex, rich interactions. Theadditional structure that arises from the rotational and vibrational degrees of freedom in diatomic molecules makes difficult the adaptation of a traditional atomic magneto-optical trap (MOT) for use with molecules, but it is a challenge that we can overcome. In order to maintain a closed rotational manifold for the optical cycling transition, one typically excites from an $N'' \rightarrow N' = N'' - 1$ rotational sublevel. This excitation scheme corresponds to a type II MOT [1]. We will present the latest results on the development of a MOT for laser cooled yttrium monoxide molecules based on a resonant LC-baseball coil geometry for a time-varying magnetic quadrupole field.

Reference
[1] A. M. L. Oien, *et. al*, Phys. Rev. A **55**, pp. 4621-4624, (1997).

Toward laser cooling of photoassociated KRb molecules

Jun Kobayashi[1,*], Masahito Ueda[2], and Shin Inouye[1]

1. School of Engineering, The University of Tokyo, Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan
2. Department of Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
**kobayashi@sogo.t.u-tokyo.ac.jp*

Recently, laser cooling of molecular beam was realized for SrF molecule by a group in Yale university[1]. The key issue for the laser cooling of molecules was to form an almost closed cycling transition by using a transition with diagonal Franck-Condon factors. Laser cooling technique of molecules could be a breakthrough for many experiments of ultracold molecules.

In our experiment, we are making ultracold KRb molecules by an indirect method, where K and Rb atoms are cooled by MOT and weekly bound molecules are formed with photoassociation from these atoms, and then the molecules are transferred into the rovibrational ground state ($X^1\Sigma^+$, v=0, N=0) by STIRAP[2]. From ab-initio calculations of molecular potentials, we found that $X^1\Sigma^+$-$b^3\Pi_0$ transition may have a narrow natural linewidth and diagonal Franck-Condon factors. Recently, we have succeeded in observing this transition. And we have experimentally determined its natural linewidth and Franck-Condon factors for (v-v′)=(0-0), (1-0) and (2-0) transitions, which are (2π) x 4.9(4) kHz, 0.948(2), 0.051(2) and 0.0013(1), respectively. Since the temperature of photoassociated molecules is as low as 135 uK, we expect that three-dimensional laser cooling of photoassociated molecules can be realized by using this transition.

References

[1] E. S. Shuman *et al.*, Nature **467**, 820 (2010).
[2] K. Aikawa *et al.*, PRL **105**, 203001 (2010).

Systematic analysis of long-range interactions between polar bialkali molecules

Romain Vexiau*, Maxence Lepers, Mireille Aymar, Olivier Dulieu, and Nadia Bouloufa

Laboratoire Aimé Cotton, CNRS, Université Paris-Sud XI, Orsay, France
**romain.vexiau@u-psud.fr*

The determination of the long-range anisotropic interaction between polar bialkali molecules is of crucial importance for the achievement of a quantum gas of ultracold polar molecules. In particular, the coefficient C_6 of the multipolar interaction depends on the dynamic polarisability of the molecule evaluated at imaginary frequencies, expressed as a sum over all possible radiative transitions of electronic dipole moments. Using a mixture of up-to-date spectroscopic data and accurate ab initio data for potential energy curves, and permanent and transition dipole moments, we have obtained the values of the coefficients between identical polar molecules (LiNa, LiK, LiRb, LiCs, NaK, NaRb, NaCs, KRb, KCs, RbCs) in an arbitrary vibrational level of their electronic ground state. For the lowest vibrational levels the C_6 parameter varies from about 10^3 atomic units for LiNa up to 10^7 atomic units for NaCs, which will lead to different collisional regimes at ultracold temperatures.

Enhancing photoassociation rates by non-resonant light control of a shape resonance

Rosario González-Férez[1,2,*] and Christiane P. Koch[3]

1. Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Spain
2. Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, Spain
3. Theoretische Physik, Universität Kassel, Kassel, Germany
**rogonzal@ugr.es*

We suggest to employ non-resonant field control of shape resonances to enhance photoassociation rates in trapped ultracold gases. Non-resonant light with intensities of the order of 10^9 W/cm^2 modifies the thermal cloud of atoms, i.e., the initial state for photoassociation. By using non resonant laser fields the energy of a shape resonance is adiabatically moved close to k_B times the trap temperature, thus enhancing its thermal weight [1]. The quasi-bound nature of the resonance wavefunction results in larger free-to-bound transition matrix elements and subsequently enhances the photoassociation rates by several orders of magnitude [2]. Results for the photoassociation rates of the Cs_2 and Sr_2 molecules will be presented as the laser intensity is varied.

References

[1] R. Aganoglu, *et al.*, *Controlling a diatomic shape resonance with non-resonant light*, arXiv:1105.0761v1, (2011).
[2] R. González-Férez and C. P. Koch, *Enhancing photoassociation rates by non-resonant light control of a shape resonance*, preprint (2012).

Production of ultracold Sr_2 molecules in the electronic ground state

Simon Stellmer[1], Benjamin Pasquiou[1,*], Rudolf Grimm[1,2], and Florian Schreck[1]

1. Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria
2. Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria
**benjamin.pasquiou@uibk.ac.at*

The creation of ultracold state controlled molecules is a promising field motivated by fundamental insights and important applications, such as precision measurements of fundamental constants, study of dipolar physic, and quantum computation. We hereby demonstrate the efficient production of ultracold molecules in the electronic ground state, without relying on a magnetic Feshbach resonance. We implement instead a STIRAP sequence, using laser frequencies near the weak $^1S_0$-$^3P_1$ intercombination line, and operating on ultracold Bose condensed ^{84}Sr atoms [1] loaded into a 3D optical lattice. For this purpose, we first perform one- and two-color photoassociation spectroscopy on the last bound vibrational levels of the excited state 0_u, 1_u and the ground state $^1\Sigma_g^+$ potentials. We then produce samples of 4×10^4 molecules, with a STIRAP efficiency of 30%. Such Sr_2 molecules are good candidates [2] for the model independent measurement of time variations of the proton-to-electron mass ratio.

References

[1] S. Stellmer *et al.*, *Bose-Einstein Condensation of Strontium*, PRL **103**, 200401 (2009).
[2] T. Zelevinsky *et al.*, *Precision Test of Mass-Ratio Variations with Lattice-Confined Ultracold Molecules*, PRL **100**, 043201 (2008).

A path integral study on a CO molecule trapped by *para*-hydrogen clusters

Kosuke Nakai and Koichi Yamashita*

Department of Chemical System Engineering, The University of Tokyo, Japan
**yamasita@chemsys.t.u-tokyo.ac.jp*

Understanding the dynamics of larger clusters CO-$(H_2)_n$ can serve as a model for molecules trapped in solid *para*-hydrogen (pH$_2$), which is useful for a range of low-temperature physics applications. Recently, we have built *ab initio* three-body potential energy surfaces for the cluster whose configuration space are sampled with coupled-cluster calculations and the three-body contributions to the nine-dimensional potential energy surface in the van der Waals well are fitted with a neural-network based method [1]. On the other hand, pH$_2$ clusters are predicted to exhibit a superfluid behaviour, however the direct observation of this phenomenon has been elusive. In experimental studies, a probe molecule is used and the increase of its effective rotational constant implies superfluidity of the system. In order to verify the validity of this criterion, it is necessary to study the behavior of molecules in the pH$_2$ cluster that is not in the superfluid state. In this study, the CO molecule is chosen as a trapped molecule and its rotational motion is traced using a path integral hybrid Monte Carlo (PIHMC) method. A cluster size dependence of the effective rotational constant is presented. It is found that the increase in rotational constants is also seen in the pH$_2$ cluster that is not in the superfluid state. This is due to the microscopic structure of the pH$_2$ cluster around the CO molecule.

Reference

[1] S. Manzhos, K. Nakai, K. Yamashita, "Three-body interactions in clusters CO-$(p\mathrm{H}_2)_n$", Chem. Phys. Lett. **493**, 229-233 (2010).

2-photon photoassociation spectroscopy in a mixture of Yb and Rb

Frank Münchow, Cristian Bruni, Ali Al-Massoudi, and Axel Görlitz

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf

Due to its paramagnetic ground state YbRb is an interesting candidate for the realization of dipolar molecules with additional degrees of freedom. Here we report on the first spectroscopic investigation of vibrational levels in the electronic ground stateof YbRb which is an important step towards the realization of YbRb ground state moelcules [1]. Using two-photon photoassociation spectroscopy in laser-cooled mixtures of ^{87}Rb and various Yb isotopes we are able to determine the binding energies of weakly-bound vibrational levels and the positions of possible magnetic Feshbach resonances. Recent theoretical work suggests that also in mixtures of alkali and spin-singlett atoms magnetic Feshbach resonances could be experimentally accessible [2]. From additional investigations by means of Autler-Townes spectroscopy we obtain information on the transition rates between vibrational levels of different electronic molecular states.

References

[1] F. Münchow, C. Bruni, M. Madalinski, and A. Görlitz. Two-photon photoassociation spectroscopy of heteronuclear YbRb. *PCCP*, 13(42):18734–18737, 2011.
[2] Piotr S. Zuchowski, J. Aldegunde, and Jeremy M. Hutson. Ultracold rbsr molecules can be formed by magnetoassociation. *Phys. Rev. Lett.*, 105(15):153201, Oct 2010.

Simple 2D permanent magnetic lattices for ultracold atoms

Abasalt Bahrami and Saeed Ghanbari*

Department of Physics, Faculty of Science, University of Zanjan 45371-38791, Zanjan, Iran
**sghanbari@znu.ac.ir*

Arrays of permanent magnetic slabs for producing 2D arrays of microtraps for trapping and controlling ultracold atoms have been introduced [1]. We propose a 2D array of square magnetic slabs which has been previously used to obtain analytical expressions for a class of permanent magnetic lattices [2]. We also, propose a more feasible magnetic lattice, consisting of the first configuration of square slabs plus a permanent magnetic substrate which holds the slabs together. In both configurations, we consider a bias magnetic field. To create Ioffe-Pritchard microtraps, the two non-zero components of the bias field in the magnetic film plane must have different values. Our analytical expressions and numerical results for different atoms are in very good agreement. The second pattern of the array of the square magnets may be fabricated using laser carving on a permanent magnetic film.

References

[1] S. Ghanbari, T. D. Kieu, A. Sidorov and P. Hannaford, *Permanent magnetic lattices for ultracold atoms and quantum degenrate gases*, J. Phys. B: At. Mol. Opt. Phys. **39**, pp. 847-860 (2006).

[2] S. Ghanbari, T. D. Kieu, and P. Hannaford, *A class of permanent magnetic lattices for ultracold atoms*, J. Phys. B: At. Mol. Opt. Phys. **40**, pp. 1283-1294 (2007).

Realization of a ^{85}Rb-^{87}Rb hetero-nuclear single atom array

Xiaodong He, Shi Yu, Peng Xu, Jin Wang, and Mingsheng Zhan*

State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China
Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
**mszhan@wipm.ac.cn*

We report a realization of determinately trapping individual isotopic ^{85}Rb and ^{87}Rb atoms in a ring shaped optical far-off resonant trap (FORT) array. The sites of the array and the species trapped in sites are fully manipulated by using a blue-detuned Laguerre-Gaussian (LG) beam[1]. The LG beam has a repulsive potential and prevents the trap already having an atom from loading a second type of atom and from light assisted atom-atom collision. Using this atomic valve, a pair of two hetero-nuclear atoms in a two-site ring lattice has been prepared with an efficiency of 90%. While we demonstrate trapping ^{85}Rb-^{87}Rb dual-species, an extension to other dual-species is straightforward. Combined with our ability to efficiently transfer the two hetero-nuclear atoms into a single FORT by using the spatial light modulator [2], this work would be a key step toward the study of ^{85}Rb-^{87}Rb collision and formation of a single hetero-nuclear dipolar molecule.

References

[1] X. D. He *et al.*, "Combining red and blue-detuned optical potentials to form a Lamb-Dicke trap for a single neutral atom", Opt. Exp., **20**, pp.3711- 3724 (2012).

[2] X. D. He *et al.*, "High efficient loading of two atoms into a microscopic optical trap by dynamically reshaping the trap with a spatial light modulator", Opt. Exp. **18**, pp.13586-13592 (2010).

Temperature measurement of cold atoms using transient absorption from an optical nanofibre

Ravi Kumar[1,*], Laura Russell[1], Mark Daly[1], Vibhuti Bhushan Tiwari[1], and Síle Nic Chormaic[1,2,3]

1. Physics Department and Tyndall National Institute, University College Cork, Cork, Ireland
2. Light-Matter Interactions Unit, Okinawa Institute of Science and Technology, Okinawa, Japan
3. School of Physics, University of Kwa-Zulu Natal, Durban 4001, South Africa
**ravi.kumar@tyndall.ie*

Optical nanofibres are effective tools for probing cold atoms in magneto-optical traps. The evanescent field arising from the light guided through the fibre interacts with atoms close to the fibre surface. Recently, the optical nanofibre has been used to measure sub-Doppler temperatures of a cold atom cloud by using forced trap oscillations [1]. Here, we study transient absorption [2] of a probe beam passing though an optical nanofibre during free expansion of a cold cloud of Rubidium-85 atoms. Using this method, the temperature of cold atoms near the surface of the fibre can be measured. The study is useful for characterizing the effect which surface interactions have on cold atoms.

References
[1] L. Russell, K. Deasy, M. Daly, M. J. Morrissey and S. Nic Chormaic, "Sub-Doppler temperature measurements of laser-cooled atoms using optical nanofibres", Meas. Sci. Tech. **23**, 015201(2012).
[2] R. R. Silva, K. M. F. Magalhães, E. A. L. Henn, L. G. Marcassa and V. S. Bagnato, "Temperature determination for magneto optical trapped atoms using a single parameter transient absorption", Opt. Commun. **265**, 526 (2006).

Beam-laser spectroscopy and optical pumping on iron atoms

N. Huet*, S. Krins, J. Crauwels, M. Pettens, and T. Bastin

Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, B - 4000 Liège, Belgium
**N.Huet@ulg.ac.be*

An original beam-laser spectroscopy set-up has been built at University of Liège. This setup allows us to produce atomic beams from samples heated in a high temperature oven. With help of laser beams crossing the atomic beam at given angles and a specific observation chamber equipped with a PM tube, a high-resolution sub-Doppler spectroscopy is obtained. We get similar resolutions to those inherent of usual laser saturation spectroscopy setups, while being able to access atomic levels otherwise unaccessible with saturation spectroscopy. Preliminary results on previously totally unknown hyperfine structure and isotopic effects for a non-resonance Iron atomic line will be presented. Our line intensities will be confronted to theoretical predictions to monitor the exact flux of atoms interacting with the laser beam. Our setup also allows for colinear optical pumping to enhance the laser absorption signals. These effects will be discussed as well, along with future prospects of our experiments.

Laser cooling of thulium atoms with Blue-Ray diodes

D. Sukachev, E. Kalganova, N. Kolachevsky, A. Sokolov, A. Akimov, and V. Sorokin

P. N. Lebedev Physical Institute, 119991 Leninskij prospekt 53, Moscow, Russia
**sukachev@gmail.com*

We have set up a laser system based on laser diodes from Blue-Ray devices operating at 410.6 nm [1]. This system consists of a master oscillator and a slave laser. The master is a Blue-Ray chip with extended resonator; output power is 20 mW and the spectral width is of 1.2 MHz. The slave laser is injection locked to the master. The system delivers 120 mW of blue light in single frequency regime. With the help of this system we demonstrate laser cooling and magneto-optical trapping of 30000 Tm atoms. Previously, laser cooling of Tm was demonstrated by a bulky frequency doubled Ti:Sapphire laser [2].

References

[1] M. Mehlhorn, Bachelor thesis, Ludwig-Maximilians-Universitaet Muenchen (2011).
[2] D. Sukachev , et. al., "Magneto-optical trap for thulium atoms", Phys. Rev. A **82**, 011405 (2010).

Simulation of the motion of ions in Paul trap

Avazeh Hashemloo*, Ghosne Elbane Rahali, and Claude Dion

Department of physics, Umeå University, SE-90187 Umeå, Sweden
**avazeh.hashemloo@physics.umu.se*

Linear Paul traps are devices that allow the confinement of charged particles using a combination of static and radio-frequency electric fields. Their elongated configurations allow for the trapping of many ions along an axis and consequently provide a suitable environment to study quantum information processing and quantum computing. We develop simulation of the classical and quantum motion of a single trapped ion in a linear Paul trap. In particular we make use of Floquet theory to reduce the problem to an effective time-independent one, based on the time periodicity of the trapping field. In addition, we derive a model for the simulation of a trapped diatomic molecular ion, where all degrees of freedom are treated quantum mechanically.

Simultaneous magneto-optical trapping of Rb and Sr

Takatoshi Aoki[1,*], Yuki Yamanaka[1], Yasuhiro Sakemi[2], and Yoshio Torii[1]

1. Institute of Physics, The University of Tokyo, Meguro, Tokyo, Japan
2. Cyclotron and Radioisotope Center, Tohoku University, Sendai, Miyagi, Japan
**aoki@phys.c.u-tokyo.ac.jp*

In recent years, there has been increasing interest in ultracold polar molecules. In particular, a molecule consisting of alkali and alkali-earth atoms has an electron spin, offering variety of research such as quantum simulators of lattice spin models. Recently, the electric dipole moment of the RbSr molecule has been predicted to be 1.36 Debye in the rovibrational ground state [1], which is advantageous to explore new quantum phases such as a crystalline phase.

We constructed an apparatus for laser cooling of Rb and Sr. For laser cooling of Sr, a 461-nm cooling beam was derived from a SHG cavity using a $KNbO_3$ crystal [2], whereas a 497-nm repumping beam was derived from a PPLN waveguide. We succeeded in simultaneous magneto-optical trapping of Rb and Sr.

References

[1] P. S. Żuchowski, J. Aldegunde, and J. M. Hutson, "Ultracold RbSr Molecules Can Be Formed by Magnetoassociation", Phys. Rev. Lett. **105**, 153201(2010).
[2] T. Aoki, K. Umezawa, Y. Yamanaka, N. Takemura, Y. Sakemi, and Y. Torii, "A 461nm Laser System and Hollow-Cathode Lamp Spectroscopy for Magneto-Optical Trapping of Sr Atoms", J. Phys. Soc. Jpn. **81** (2012) 034401.

Large Sr^+ Coulomb crystals: isotopic enrichment and single-pass absorption

B. Dubost, S. Guibal, L. Guidoni, and J.-P. Likforman*

Université Paris–Diderot, Sorbonne Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162 CNRS, F-75205 Paris, France
**jean-pierre.likforman@univ-paris-diderot.fr*

We present the realization of large Coulomb crystals containing up to 5×10^6 strontium ions. This kind of sample has potential applications in different fields such as quantum information [1] and cold-molecule spectroscopy [2]. Our experiment is based on a linear Paul trap loaded by photo-ionization of a strontium atomic vapor using ultrafast pulses allowing for the formation of large multi-isotope Sr+ Coulomb crystals. We also present a method for controlling the ratio between the various strontium isotopes in the ion crystals. For example we realized pure crystals (of $^{88}Sr^+$, $^{86}Sr^+$, and $^{84}Sr^+$ which has a natural abundance of 0.6%) as well as two-isotope crystals (e.g. $^{86}Sr^+ + {}^{84}Sr^+$). Coulomb crystals containing two spatially segregated isotopes have applications in quantum information experiments in which one isotope sympathetically cools a second isotope fully available for quantum manipulation. We also present preliminary measurements of single-pass absorption realized in such atomic samples.

References

[1] T. Coudreau, F. Grosshans, S. Guibal, L. Guidoni, *Feasibility of a quantum memory for continuous variables based on trapped ions: from generic criteria to practical implementation*, J. Phys. B: At. Mol. Opt. Phys. **40**, 413 (2007).
[2] X. Tong, A. H. Winney, and S. Willitsch, *Sympathetic Cooling of Molecular Ions in Selected Rotational and Vibrational States Produced by Threshold Photoionization*, Phys. Rev. Lett. **105**, 143001 (2010).

Towards ground state electron guiding on a surface electrode microwave chip

Jakob Hammer*, Johannes Hoffrogge, and Peter Hommelhoff

Max Planck-Institut of Quantum Optics, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
**jakob.hammer@mpq.mpg.de*

We investigate the guiding of electrons in a miniaturized planar ac-quadrupole guide (linear Paul trap) [1]. Electrons propagating freely along electrodes on a micro-fabricated chip experience a tight transverse harmonic confinement. For our guiding parameters the dimensions of the quantum mechanical ground state of the guiding potential is still resolvable by electron optics. This encourages experiments to prepare electrons in the transverse motional ground state by matching the wavefunction of an incident electron with the ground state of the microwave guide. Here we report on our ongoing experimental efforts. We use a single-atom tip electron emitter, a point source for electrons producing an exceptionally bright and fully coherent electron beam, for injection into the guide. Efficient ground state coupling requires a spot size of ~ 100 nm and an angular spread of ~ 1 mrad of the incoming electron wavefunction. For collimation of the electron wavepacket right after emission we are fabricating a sub-micron electrostatic lens. We present the current status of the experiment as well as numerical simulations on quantum mechanical electron wavefunction propagation. In this context electron guiding represents an ideal starting point for guided matter-wave interferometry and controlled electron-electron or electron-surface interactions where the quantum mechanical states of the guide serves as carrier of quantum information.

Reference

[1] J. Hoffrogge, R. Fröhlich, M. Kasevich and P. Hommelhoff, *Phys. Rev. Lett.* **106**, 193001 (2011).

Sympathetic cooling of ions by ultracold Na atoms in a hybrid trap

Winthrop Smith[1,*], Douglas Goodman[1], Ilamaran Siverajah[1], James E. Wells[1], and F. A. Narducci[2]

1. Physics Department, University of Connecticut, Storrs, CT, 06269-3046, USA
2. Naval Air Systems Command, EO Sensors Division, Patuxent River, Maryland 20670, USA
**winthrop.smith@uconn.edu*

Laser cooling atoms to ultracold temperatures has opened a new fruitful regime for atomic physics. Closed shell atomic ions, such as Na^+, and nearly all molecular ions lack the optical transitions that are required for laser cooling, precluding their use in a variety of experiments, including near zero-K reaction studies and applications such as quantum gates. We have created a hybrid atom-ion trap system to cool atomic or molecular ions which cannot be laser cooled [1]. It consists of a magneto-optic trap (MOT) for Na, concentric with a linear Paul r.f. ion trap [2,3]. Recent simulations we have carried out using SIMION 7 show that cold MOT atoms may be used to sympathetically cool hot ions to sub-Kelvin temperatures. We have found experimental evidence of this: trapped Na+ ions exposed to the MOT have extended lifetimes in the Paul trap. We have studied secular frequency quenching of unwanted ions (e.g. Na_2+) from the Paul trap, without disturbing the trapped Na^+ ions.

References

[1] W. Smith, E. Babenko, R. Cote' and H. Michels, in Coherence and Quantum Optics, VIII, N. Bigelow, *et al.*, eds., Kluwer Academic Publ., NY 2003, pp. 623-624.
[2] W. Smith, *et al.*, J. Modern Optics 52, pp. 2253-2260 (2005).
[3] E. R. Hudson, Phys. Rev. A 79, 032716 (2009) and references therein to related work.

Effects of a non-Gaussian profile intensity beam in a magneto-optical trap

Anne Luise Krüger[1,3], Ricardo Antonio De Simone Zanon[1,3], Vanderlei Salvador Bagnato[2,3], and André Luiz de Oliveira[1,3,*]

1. Departamento de Física, Universidade do Estado de Santa Catarina,Joinville, SC, Brazil
2. Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil
3. Instituto Nacional de Óptica e Fotônica, INOF/CNPq, Brazil
**andre.oliveira@udesc.br*

The magneto-optical traps allow cooling and trapping of atoms. Some of the possible applications for the cold atoms are: spectroscopy of ultra-high resolution, atomic clocks and the achievement of Bose-Einstein condensate [1]The purpose of our research is to study the behaviour of the movement of atoms by varying some parameters of the trap, such as gradient magnetic field, the intensity of laser beams, the detuning and the intensity profile of the beams. Simulations were conducted to describe the behaviour of the trajectory of an atom under the influence of the forces present in a magneto-optical trap in the case of using beams with non-Gaussinan profile, it was also necessary to deduce the force equation taking into account a new general intensity profile, calculated as follows:

$$I = I_0\left(1-\left(\frac{y}{a}\right)^n\right)$$

It is possible to obtain clouds of the atoms in a ring, by using a beam intensity profile different from the Gaussian. Moreover, it is clear that the cloud of atoms in this new configuration becomes smaller.

Reference

[1] S. Bize, et. al. J. of Phys. B , 449(2005); M. H. Anderson et. al., Science **269**, 198 (1995).

Generation of a decoherence-free entangled state using a radio-frequency dressed state

Atsushi Noguchi*, Shinsuke Haze, Kenji Toyoda, and Shinji Urabe

Graduate School of Engineering Science, Osaka University, Osaka, Japan
**noguchi@qe.ee.es.osaka-u.ac.jp*

A noisy environment induces unwanted disturbances to quantum states and leads to decoherence. From this point of view, a decoherence-free subspace (DFS) is well known to prolong the coherence time. In particular, a DFS using a dressed state [1] ("dressed DFS") has the advantage that quantum states are protected even in the presence of a stray magnetic field gradient, which often limits the coherence time in a traditional DFS [1]. If qubits are globally exposed to an external field (dressing field), a Dicke ladder is constructed. States on the Dicke ladder whose projections of total angular momentum are zero can be used to construct the dressed DFS.

We demonstrate dressed decoherence-free entangled state [2] i.e. a logical qubit in dressed DFS using a combination of a dressed state of rf qubits and an Mølmer-Sørensen interaction. The coherence time of this entangled state is increased by about 2 orders of magnitude with the protection of rf dressing field.

References

[1] N. Timoney, et. al., *Quantum gates and memory using microwave-dressed states.* Nature **476**, 185 (2011).
[2] A. Noguchi, et. al., *Generation of a Decoherence-Free Entangled State Using a Radio-Frequency Dressed State* Phys. Rev. Lett. **108**, 060503 (2012).

Towards ultracold mixtures on an atom chip

Sonali Warriar, Asaf Paris-Mandoki, Matt Jones,
Peter Krüger, and Lucia Hackermuller*

University of Nottingham, UK
**Lucia.Hackermuller@nottingham.ac.uk*

Ultracold mixtures hold the promise of understanding new phases of matter and collisions at very low energies. By combining the capabilities of the atom chip with optical dipole trapping, it will be possible to trap these mixtures in low dimensions and tune their scattering lengths via Feshbach resonances. In this way it will also be possible to realise experiments with additional magnetic potentials, position dependent interactions or impurity dynamics. Here we present the current status of our Lithium and Cesium experiment. We detail the cooling schemes for both atom species and include the recent development of implementing an optical dipole trap. We discuss ideas for future measurements with separately addressable Bose-Fermi mixtures in optical dipoletraps, such as transport and impurity studies in low dimensions, close to a chip surface.

Cooling and trapping… Tu-190

A versatile collider for ultracold atoms

Ana Rakonjac, Amita Deb, Bianca Sawyer, Thomas McKellar, and Niels Kjærgaard*

Jack Dodd Centre for Quantum Technology,
Department of Physics, University of Otago, Dunedin, New Zealand
**niels.kjaergaard@otago.ac.nz*

We report on the progress on a laser based accelerator for studying cold collisions between ultracold atoms. Such miniature colliders may for example open up routes to study Efimov physics via the collision energy dependence of three-body scattering observables [1] and to implement “hard probes” for strongly interacting gases. Having demonstrated and characterized the working principle of the optical collider [3] using ^{87}Rb atoms in the $|F=2,m_F=2\rangle$ ground state, we are presently extending the scheme to multiple internal quantum states and to collisions between different atomic species. With a scheme based on laser confinement and acceleration an external magnetic field can be exploited to tune atomic interactionsand scattering experiments can be conducted at fixed collision energies into the millikelvin (measured in units of the Boltzmann constant) regime with nanokelvin samples.

References

[1] Y. Wang, J. P. D’Incao, H.-C. Nägerl, and B. D. Esry, *Colliding Bose-Einstein Condensates to Observe Efimov Physics*, Phys. Rev. Lett. **104**, 113201 (2010).
[2] Y. Nishida, *“Hard probes” of strongly-interacting atomic gases*, arXiv:1110.5926 (2011).
[3] A. Rakonjac, A. B. Deb, S. Hoinka, D. Hudson, B. J. Sawyer, and N. Kjærgaard, *Laser based accelerator for ultracold atoms*, Opt. Lett. **37**, 1085 (2012).

Fundamental atomtronic circuit elements

Jeffrey G. Lee, Brian J. McIlvain, Christopher J. Lobb, and Wendell T. Hill, III*

Joint Quantum Institute, University of Maryland, College Park, MD 20742, USA
**wth@umd.edu*

Recent experiments have demonstrated steps toward creating neutral atom analogs to superconducting circuits[1]. The goals of these experiments are to create complex systems like Josephson junctions. For these devices to function, an understandingof the more fundamental atomtronic elements is also needed. We describe the first experimental realization of these fundamental elements. We have created an atom analog to a capacitor that we discharged through a resistor and inductor. We derive theoretical values for the capacitance, resistance and inductance, showing them to be analogous to the quantum capacitance[2], Sharvin resistance[3] and kinetic inductance[4] found in condensed matter. This atomtronic circuit is implemented in a thermal sample of laser cooled rubidium atoms. The atoms are confined using free-space atom chips, a novel optical dipole trap produced using a generalized phase-contrast imaging technique. We also discuss current progress in extending this work to a sodium BEC.

References

[1] A. Ramanathan *et al.*, *Superflow in a Toroidal Bose-Einstein Condensate: An Atom Circuit with a Tunable Weak Link*, Phys. Rev. Lett. **106**, pp. 130401 (2011).
[2] S. Luryi, *Quantum capacitance devices*, Appl. Phys. Lett. **6**, pp. 501 (1988).
[3] A. G. M. Jansen *et al.*, *Point-contact spectroscopy in metals*, J. Phys. C: Solid State Phys. **13**, pp. 6073-6118 (1980).
[4] A. M. Kadin, *Introduction to Superconducting Circuits*, New York: John Wiley and Sons (1999).

Doppler cooling of multilevel-level systems by the coherent pulse trains

Ekaterina Ilinova, Mahmoud Ahmed, and Andrei Derevianko

University of Nevada, Reno, NV, USA

Direct application of the conventional Doppler cooling to multilevel atoms and molecules is challenging: most atoms and all molecules have transitions that can radiatively branch out to a multitude of other states. Exciting population from all these lower-energy states requires a large number of lasers which makes the conventional scheme impractical. Here we explore an alternative scheme: cooling with trains of ultrashort laser pulses. Frequency comb (FC) spectrum generated by the pulse train can drive many transitions simultaneously. Positions and intensities of individual FC teeth can be manipulated by pulse shaping techniques. Recently we demonstrated that the ensembles of two- and three-level systems can be effectively cooled by such trains [1]. As a result of cooling, atomic velocity distribution gravitates towards "velocity comb": a series of narrow groups of atomic velocities separated by λ_c / T, where λ_c is the carrier wave length and T is the pulse repetition period. Here we report our theoretical results on Doppler cooling multilevel systems with coherent trains of shaped laser pulses.

Reference

[1] E. Ilinova, A. Derevianko, *Doppler cooling of three-level Λ-systems by coherent pulse trains*, http://arxiv.org/abs/1203.1963 (2012).

Excited state spatial distributions in a cold strontium gas

G. Lochead*, D. Boddy, D. Sadler, C. S. Adams, and M. P. A. Jones

Durham University, Durham, UK
**graham.lochead@durham.ac.uk*

Long-range interactions between Rydberg atoms in cold atom ensembles lead to spatial correlations that are not present in the ground state distribution [1, 2]. We aim to study these correlations using a scanning autoionising microscopy technique. We excite a cloud of Sr atoms cooled to 5mK to a Rydberg state via a resonant two-photon transition using narrowband CW lasers. Working with strontium means there is a second valence electron with a transition at an accessible optical wavelength. Excitation of this electron leads to autoionisation of the atom. Previously we have used the fact that the autoionisation spectrum is dependent upon the atomic state of the Rydberg atom to study the population transfer mechanics caused by the onset of plasma formation [3]. By translating a tightly focused autoionisation laser across the ensemble we have extended the technique to measure the spatial distribution of the Rydberg atoms. We present preliminary measurements of the 2D Rydberg state spatial distribution.

References

[1] M. Lukin *et al.*, *Dipole blockade and quantum information processing in mesoscopic atomic ensembles*, Phys. Rev. Lett. **84**, 037901 (2001).
[2] T. Pohl, E. Demler, and M. D. Lukin, *Dynamical Crystallization in the Dipole Blockade of Ultracold Atoms*, Phys. Rev. Lett. **104**, 043002 (2010).
[3] J. Millen, G. Lochead and M. P. A. Jones, *Two-electron excitation of an interacting cold Rydberg gas*, Phys. Rev. Lett. **105**, 213004 (2010).

From two body… Tu-194

Rf spectroscopy of the Efimov energy level

Olga Machtey, Zav Shotan, Noam Gross, and Lev Khaykovich

Department of Physics, Bar-Ilan University, Ramat-Gan, 52900 Israel

We develop an experimental technique for rf association of Efimov trimers from a three-atom continuum. We apply it to probe the lowest accessible Efimov energy level in bosonic lithium in the region where strong deviations from the universal behavior are expected, and provide a quantitative study of this effect. Our measurements indicate a shifted position of the Efimov resonance at the atom-dimer threshold as compared to the universal theory prediction. The result of a different experimental technique concurs with the rf association measurements. This technique explores secondary collisions of the dimer, formed in a three-body recombination, which cross-sections are expected to increase in the vicinity of the Efimov resonance. We developed a model that counts the number of elastic and inelastic collisions of a dimer with trapped atoms based on the available analytical expressions for the cross-sections of these events. We show shift in the position of the secondary collisions' enhancement for large collisional opacities.

References

[1] O. Machtey, Z. Shotan, N. Gross, and L. Khaykovich, "Association of Efimov trimers from a three-atom continuum", arXiv:1201.2396.
[2] O. Machtey, D. A. Kessler, and L. Khaykovich, "Universal Dimer in a Collisionally Opaque Medium: Experimental Observables and Efimov", Phys. Rev. Lett. **108**, 130403 (2012).

Observation of ferromagnetic spin correlations in a 1D Fermi system

Thomas Lompe[1,2,*], Gerhard Zürn[1,2], Andre Wenz[1,2], Vincent Klinkhamer[1,2], Andrea Bergschneider[1,2], Simon Murmann[1,2], and Selim Jochim[1,2]

1. Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Germany
2. Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
**thomas.lompe@mpi-hd.mpg.de*

One of the simplest models used to explain ferromagnetism of delocalized spin 1/2 fermions is the Stoner model, which predicts a transition to a ferromagnetic state when the strength of the repulsive interaction exceeds the Pauli repulsion between identical fermions. Here we report on our studies of a quasi one-dimensional system of ultracold fermionic ^{6}Li atoms in two different hyperfine states. For such a 1D system it has been shown that the Stoner transition to ferromagnetism does not occur for a finite strengthof the repulsive interaction. We start from ground-state systems of three to five particles and tune the interaction strength across $\pm\infty$ using a Feshbach resonance. This allows us to create long-lived metastable states in which the energy of theinteracting spin $\left|\uparrow\downarrow\right\rangle$ system is larger than energy of the corresponding spin-polarized system. We probe the spin-spin correlations in the system by letting a fraction of the particles escape from the trap and measuring the total spin of the remaining ensemble. For the metastable branch across the resonance we find a strong enhancement in the number of spin polarized systems created by the spilling process, which signals the appearance of ferromagnetic correlations.

Universality and the three-body parameter of helium-4 trimers

Pascal Naidon[1,*], Emiko Hiyama[1], and Masahito Ueda[2]

1. RIKEN, Wako, Japan
2. The University of Tokyo, Tokyo, Japan
**contact.pascal@riken.jp*

We consider a system of three helium-4 atoms, which is so far the simplest realistic three-body system exhibiting the Efimov effect [1], in order to analyse deviations from the universal Efimov three-body spectrum. We first calculate the bound states using a realistic two-body potential, and then analyse how they can be reproduced by simple effective models beyond Efimov's universal theory.

We find that the non-universal variations of the first two states can be well reproduced by models parametrized with only three quantities: the scattering length and effective range of the original potential, and the strength of a small three-body force. Furthermore, the three-body parameter which fixes the origin of the infinite set of three-body levels is found to be consistent with recent experimental observations in other atomic species.

Reference

[1] F. Ferlaino, R. Grimm, Physics 3 (2010) 9.

Exploration into ultra cold chemistry: few-body calculation in Bose-Fermi mixture

Chen Zhang*, Javier von Stecher, Jose D'Incao, and Chris H. Greene

JILA, university of Colorado, Physics department
**cz@jilau1.colorado.edu*

This project investigates the properties of fermionic molecules ^{87}Rb^{40}K, including (i) its formation from a mixed gas of bosonic ^{87}Rb and fermionic ^{40}K through magnetic field ramping and (ii) its scattering properties after formation, which sheds light on both the formation and decay processes of the fermionic molecules. We mainly approach this from a few-body perspective: the spectrum of two bosons (^{87}Rb) and two fermions (^{40}K) is first calculated in a harmonic trap using a standard correlated-Gaussian basis throughout the range of a broad Fano-Feshbach resonance. We also perform hypherspherical correlated-Gaussian calculation of the adiabatic hyperspherical potential curve describing the bose-fermi mixture system at various scattering lengths. The single channel calculation and multi-channel calculation provide effective dimer-atom scattering lengths and trimer-atom scattering lengths as well as the dimer-dimer scattering phase shift.The avoided crossings in the hyperspherical potential curves of the few-body system enables an interpretation of the scattering dynamics of the bose-fermi mixture system. This single- and multi-channel scattering calculation shows agreement with the zero-range potential calculation in a harmonic trap [1, 2].

References

[1] B. Bogdan and D. Blume and Chris H. Greene, New J. Phy. **5**, 1 (2003), 111.
[2] T. Busch, B. Englert, K. Rzazewski and M. Wilkens, **28**, 4 (1998), 549-559.

Investigating magnetic field near a superconducting atom chip with cold atoms

Tetsuya Mukai

NTT Basic Research Laboratories, Atsugi, Japan
tetsuya@nttbrl.jp

Magnetic field near a superconducting atom chip and an interaction between cold atoms and the cryogenic surface of a superconductor have yet to be observed. In this paper an experimental study is made of the magnetic field near a superconducting Nb disc with cold Rb atoms. When a superconducting disc in a pure state is exposed to a perpendicular magnetic field, a funnel-form potential with a field minimum at the center of the disc surface appears and atoms released in the potential are temporally accumulated near the surface. When the disc temperature is set lower than the dendritic instability temperature the magnetic flux penetration is observed with inhomogeneously distributed atomic clouds near the surface. A change in the magnetic flux distribution is triggered depending on the disc temperature at which a magnetic field is applied.

Reference

[1] Tetsuya Mukai, *Investigating magnetic field near a superconducting disc with cold atoms*, in preparation.

Conversion of bright magneto-optical resonances into dark by changing temperature at fixed laser frequency for D_2 excitation of atomic rubidium

M. Auzinsh, A. Berzins*, R. Ferber, F. Gahbauer, L. Kalvans, A. Mozers, and D. Opalevs

Laser Centre, The University of Latvia, LV-1586 Riga
**andris.beerzinsh@gmail.com*

We present experimental results and theoretical predictions of magneto-optical resonances changing from bright to dark resonances as a result of temperature changes when excited by circularly polarized light at the D_2 transition of rubidium in natural mixture [1]. As the temperature was increased, the contrast of the bright resonance decreased until the bright resonance disappeared at around 40^0C. At this temperature, the optical depth traversed by the laser beam in the 25-mm-long cell was ~ 0.39. At higher temperatures, a dark resonance was observed, and its contrast grew with increasing temperature. The change from bright to dark resonance around an optical depth of 0.66 is probably related to reabsorption. With each reabsorption cycle, information about the original coherent atomic state is lost. At linearly polarized excitation substantial changes in the resonance profile also were observed, although the resonance remained dark over the entire range of accessible temperatures.

Reference

[1] M. Auzinsh *et al.* "Conversion of bright magneto-optical resonances into dark resonances at fixed laser frequency for D_2 excitation of atomic rubidium", PHYSICAL REVIEW A 85, 033418 (2012).

Effects of dark state formation in the hyperfine excitation spectra of Na atoms

D. Efimov[1], M. Bruvelis[2], J. Ulmanis[2,3], K. Miculis[2], N. Bezuglov[1,2], T. Kirova[2], and A. Ekers[2,*]

1. Faculty of Physics, St. Petersburg State University, St. Petersburg, Russia
2. Laser Centre, University of Latvia, Riga, Latvia
3. University of Heidelberg, Institute of Physics, Heidelberg, Germany
**aigars.ekers@lu.lv*

We consider the formation of dark states upon interaction of hyperfine level systems with strong laser fields [1]. Sodium $3S_{1/2}$,F'' = 1,2 $3S_{1/2}, F''=1,2$ and $3P_{1/2}, F'=1,2$ levels are coupled by a strong S-laser field with Rabi frequency Ω_S forming the laser-dressed states. The latter are monitored by scanning a weak probe field across the $3P_{1/2}, F=1,2 \rightarrow 7D_{3/2}$ transition. The excitation spectrum of the $7D_{3/2}$ state shows the presence of an intense main peak with side peaks of much smaller intensities. The increase of Ω_S shifts the the side-peaks further apart, while the position of the main peak is hardly affected. These observations are explained in the dressed-state formalism; depending on the S-field detuning either F'' = 1 or F'' = 2 component of the ground state is coupled to the two $F'=1,2$ levels of $3P_{1/2}$. We show that the such system exhibits a visible "gray" state whose eigenvalue is weakly affected by the magnitude of Ω_S. This gray state evolves into a dark state at high Ω_S.

We acknowledge support by the EU FP7 Centre of Excellence project FOTONIKA-LV and IRSES Project COLIMA.

Reference

[1] J. S. Morris and B. W. Shore, *Reduction of degenerate two-level excitation to independent two states system*, Phys. Rev. A **27**, pp. 906-912 (1983).

Suppression of excitation channels by composite pulse sequences

Genko Genov* and Nikolay Vitanov

Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria
**genko.genov@phys.uni-sofia.bg*

We present a method for suppression of unwanted excitation channels in specific multistate quantum systems by the application of composite pulse sequences. By making suitable choices for the phases of the constituent pulses, we suppress excitation channels even when the couplings between the corresponding states are different from zero. Compensation with respect to deviations in polarization, pulse area, and detuning are demonstrated. The accuracy of the proposed technique, its experimental feasibility, and its robustness make it suitable for various physical applications in quantum information processing and quantum optics.

Optimal control of a few atoms in a bipartite superlattice

Wenhua Hai, Kuo Hai, and Qiong Chen

Department of Physics, Hunan Normal University, Changsha 410081, China

For a single particle held in a bipartite superlattice with two different separations and under a external driving of arbitrary shape, we construct analytical solutions in the nearest-neighbour tight binding approximation, through a discrete Fourier transformation. By optimally designing the driving shapes, the analytical solutions are adopted to quantitatively describe and control transport characterizations of the particle. Take the biperiodic driving, Rosen-Zener pulse and Gaussian pulse as examples, the selective coherent destruction of tunneling (SCDT) and dynamic localization are found, which are applied to coherent manipulations of the directed motion and Rabi oscillation. The results could be extended to few-particle case and are useful for transporting quantum information carried by the particles in a bipartite superlattice material or a bipartite optical lattice.

References

[1] L. Guidoni and P. Verkerk, “Direct observation of atomic localization in optical superlattices”, Phys. Rev. A57, R1501 (1998).
[2] C. E. Creffield, “Quantum Control and Entanglement using Periodic Driving Fields”, Phys. Rev. Lett. 99, 110501 (2007).
[3] Kuo Hai, Wenhua Hai, and Qiong Chen, “Controlling transport and entanglement of two particles in a bipartite lattice”, Phys. Rev. A82, 053412 (2010).
[4] Kuo Hai, Qiong Chen, and Wenhua hai, “Instability inducing directed tunneling of a single particle in a bipartite lattice”, J. Phys. B44, 035507(2011).

Optical repumping of triplet-P states enhances magneto-optical trapping of ytterbium atoms

Chang Yong Park[2,**], Jun Woo Cho[1], Hangyeol Lee[1], Sangkyung Lee[1], Jaewook Ahn[1,*], Won-Kyu Lee[2], Dai-Hyuk Yu[2], and Sun Kyung Lee[2]

1. Department of Physics, KAIST, Daejeon 305-701
2. Korea Research Institute of Science and Standards, Daejeon 305-340, Korea
**jwahn@kaist.ac.kr*
***cypark@kriss.re.kr*

Radiative decay from the excited $^1P_1$ state to metastable $^3P_2$ and $^3P_0$ states is expected to limit the attainable trapped atomic population in a magneto-optic trap of ytterbium (Yb) atoms. In experiments we have carried out with optical repumping of $^3P_{0,2}$ states to $^3P_1$, we observe an enhanced yield of trapped atoms in the excited $^1P_1$ state. The individual decay rate to each metastable state is measured and the results show excellent agreement with the theoretical values.

References

[1] T. Loftus, J. R. Bochinski, R. Shivitz, and T. W. Mossberg, Phys. Rev. A 61, 051401(R) (2000).
[2] S. G. Porsev, Y. G. Rakhlina, and M. G. Kozlov, Phys. Rev. A 60, 2781 (1999).
[3] K. Honda, Y. Takahashi, T. Kuwamoto, M. Fujimoto, K. Toyoda, K. Ishikawa, and T. Yabuzaki, Phys. Rev. A 59, R934 (1999).

Development of perturbed relativistic coupled-cluster theory for the calculation of electric dipole polarizability of closed-shell systems

S. Chattopadhyay[1,*], B. K. Mani[2], and D. Angom[1]

1. Physical Research Laboratory, Ahmedabad 380009, Gujarat, India
2. Department of Physics, University of South Florida, Tampa, Florida 33620, USA
**sidhu@prl.res.in*

The coupled-cluster theory is one of the most reliable quantum many-body theory [1]. In the present work, we have developed perturbed relativistic coupled-cluster (PRCC) theory [2] to incorporate the effect of external electric field as a perturbation in the atomic many-body calculations. For this, the coupled-cluster equations of the singles and doubles cluster operators are derived and the contributing diagrams are examined. These diagrams are further evaluated using angular momentum algebra. The PRCC operators, obtained by solving the coupled non-linear equations, are then used for the dipole polarizability calculation of closed-shell systems. In this poster, we will present results of electric dipole polarizability of noble gas atoms using the PRCC theory.

References

[1] F. Coester, *Bound states of a many-particle system*, Nucl. Phys. **7**, 421 (1958).
[2] B. K. Mani and D. Angom, *Relativistic coupled-cluster theory of nuclear spin-dependent parity non-conservation*, arXiv:1105.3447v2 (2011)

Hyperfine frequency shift and Zeeman relaxation in alkali vapor cells with anti-relaxation alkene coating

Eric Corsini[1,*], Mikhail Balabas[2], Todor Karaulanov[1], and Dmitry Budker[1,3]

1. University of California, Berkeley, CA, 94720, USA
2. Vavilov State Optical Institute, St Petersburg, Russia
3.Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA
**eric.corsini@gmail.com*

A recently identified alkene based anti-relaxation coating exhibit Zeeman relaxation times in excess of 60 s in alkali vapor cells (two orders of magnitude longer than in paraffin coated cells) [1]. The long relaxation times, motivate revisiting the long-standing question of what is the mechanism underlying wall-collision induced relaxation and renew interest in applications of alkali vapor cells to secondary frequency standards. We measure the Zeeman relaxation time, and the width and frequency shift of the clock resonance, in ^{85}Rb and ^{87}Rb vapor cells with alkene anti-relaxation coating. in paraffin coated cells. We find that the frequency shift is slightly larger than for paraffin coated cells. However we observe that the Zeeman relaxation rate appears to be a linear function of the hyperfine frequency shift, whereas a linear dependence was not observed in paraffin coated cells. To shed light on this result we propose a model describing different Zeeman relaxation mechanisms of alkene and alkane cell-wall coatings.

Reference

[1] M. V. Balabas, T. Karaulanov, M. P. Ledbetter, and D. Budker. *Polarized Alkali-Metal Vapor with Minute-Long Transverse Spin-Relaxation Time*, Phys. Rev. Lett.**105**, pp. 7 (2010).

Programmable trap geometries with Superconducting atom chips

Mirco Siercke[1,2,*], Kin Sung Chan[2], Bo Zhang[1,2], Mussie Beian[1,2], Michael J. Lim[3], and Rainer Dumke[1,2]

1. Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore
2. Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore
3. Department of Physics, Rowan University, 201 Mullica Hill Road, Glassboro, NJ 08028, USA
**cqtmirco@nus.edu.sg*

The use of superconductors in atom chips is a recent development, presenting new opportunities for atom optics [1, 2]. One demonstrated advantage of superconductors over conventional conductors is the significant reduction of near-field noise in current-carrying structures, leading to low atomic heating rates and enhanced spin-flip lifetimes [3]. We demonstrate the trapping of ultracold atoms in the magnetic field formed entirely by persistent supercurrents induced in a thin film type-II superconducting square. The supercurrents are carried by vortices induced in the 2D structure by applying two magnetic field pulses of varying amplitude perpendicular to its surface. This results in a selfsufficient trap which does not require any externally applied fields. To demonstrate possible applications of these types of supercurrent traps we show how a central quadrupole trap can be split into four traps by use of a bias field.

References

[1] T. Müller, B. Zhang, R. Fermani, K. S. Chan, Z. W. Wang, C. B. Zhang, M. J. Lim and R. Dumke, *Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure*, New Journal of Physics **12**, 043016 (2010).
[2] T. Müller, B. Zhang, R. Fermani, K. S. Chan, M. J. Lim and R. Dumke, *Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure*, Phys. Rev. A **81**, 053624 (2010).
[3] R. Fermani, T. Müller, B. Zhang, M. J. Lim, and R. Dumke *Heating rate and spin flip lifetime due to near-field noise in layered superconducting atom chips*, J. Phys. B **43**, 095002 (2010).

Hybrid atom-membrane optomechanics

M. Korppi[1], S. Camerer[2], A. Jöckel[1], D. Hunger[2], T. W. Hänsch[2], and P. Treutlein[1,*]

1. Department of Physics, University of Basel, Switzerland
2. Max-Planck-Institute of Quantum Optics and LMU Munich, Germany
**philipp.treutlein@unibas.ch*

In optomechanics, laser light is used for cooling and control of the vibrations of micromechanical oscillators, with many similarities to the cooling and trapping of atoms. It has been proposed that laser light could also be used to couple the motion of atoms in a trap to the vibrations of a mechanical oscillator [1]. In the resulting hybrid optomechanical system the atoms could be used to read out the oscillator, to engineer its dissipation, and ultimately to perform quantum information tasks.

We have realized a hybrid optomechanical system by coupling ultracold atoms to a micromechanical membrane [2]. The atoms are trapped in an optical lattice, formed by retro-reflection of a laser beam from the membrane surface, resulting in optomechanical coupling as proposed in [1]. We observe both the effect of the membrane vibrations onto the atoms as well as the backaction of the atomic motion onto the membrane. By coupling the membrane to laser-cooled atoms, we engineer the dissipation rate of the membrane. This mechanism can be used to sympathetically cool the membrane with the atoms.

References

[1] K. Hammerer, K. Stannigel, C. Genes, P. Zoller, P. Treutlein, S. Camerer, D. Hunger, and T. W. Hänsch, Phys. Rev. A **82**, 021803 (2010).
[2] S. Camerer, M. Korppi, A. Jöckel, D. Hunger, T. W. Hänsch, and P. Treutlein, Phys. Rev. Lett. **107**, 223001 (2011).

Cavity optomechanics with micromirrors and nanomembranes

A. G. Kuhn[1,*], T. Antoni[1,2], K. Makles[1], E. van Brackel[1], L. Neuhaus[1], J. Teissier[1], S. Deléglise[1], T. Briant[1], P.-F. Cohadon[1], and A. Heidmann[1]

1. Laboratoire Kastler Brossel, ENS-UPMC-CNRS, Paris, France
2. Laboratoire de Photonique et Nanostructures, CNRS, Marcoussis, France
**aurelien.kuhn@spectro.jussieu.fr*

Reaching the quantum ground state of a macroscopic mechanical object is a major experimental challenge in physics, at the origin of the rapid emergence of cavity optomechanics. We developed a new generation of optomechanical devices, either based on microgram 1-mm long quartz micropillar with very high mechanical quality factor (10^6) [1], or on 100-pg photonic crystal suspended nanomembranes [2]. Both are used as end mirror in a Fabry-Perot cavity with a high optical finesse(up to 50 000) leading to ultra-sensitive interferometric measurement of the resonator displacement. We expect to reach the ground state of such optomechanical resonators combining cryogenic cooling with a dilution fridge at 30 mK and radiation-pressure cooling [3]. We already carried out a quantum-limited measurement of the micropillar thermal noise at low temperature, and the cold damping of the nanomembrane.

References

[1] A. G. Kuhn *et al.*, *A micropillar for cavity optomechanics*, App. Phys. Lett. **99**, 121103 (2011).
[2] T. Antoni *et al.*, *Deformable two-dimensional photonic crystal slab for cavity optomechanics*, Opt. Letters **36**, 3434 (2011).
[3] O. Arcizet *et al.*, *Radiation-pressure cooling and optomechanical instability of a micromirror*, Nature **444**, 71 (2006).

Long-range gravitational-like interaction in a neutral cold gas

M. Chalony[1], A. Olivetti[2], B. Marcos[2], J. Barré[2], and D. Wilkowski[1,3,4,*]

1. INLN, Université de Nice Sophia-Antipolis, CNRS, 06560 Valbonne, France
2. LJAD, Université de Nice Sophia-Antipolis, CNRS, 06109 Nice, France
3. CQT, National University of Singapore , 117543 Singapore, Singapore
4. PAP, SPMS, Nanyang Technological University, 637371 Singapore, Singapore
**david.wilkowski@ntu.edu.sg*

The equilibrium characteristic of gravitational systems is theoretically well established. For example it has been shown that particular phase transition occurs in the presence of non-additive long range interaction. In this context microcanonical and canonical ensembles are not anymore equivalent. This situation is in striking contrast with the experimental side of the subject where there is, so far, no controllable experimental system. We have recently show some experimental evidences of a gravitational-like interaction on an one-dimensional test system consisting in a cold gas of neutral Strontium atoms. For that purpose, two counter-propagating laser beams are tuned on the narrow intercombination line. In particular, we found that the density profile follows the expected $1/\cosh^2$ law and the relaxation dynamic of the cold gas is modified by the long range interaction.

Towards room-temperature electron spin detection in biological systems

Nicholas Chisholm[1,*], Igor Lovchinsky[1], Alex Sushkov[1], Peggy Lo[1], Minako Kubo[1], Eric Bersin[1], Norman Yao[1], Steven Bennett[1], David Hunger[2], Alexey Akimov[3], Amy Sutton[1], Hongkun Park[1], and Mikhail Lukin[1]

1. Harvard University, Cambridge, USA
2. Max-Planck-Institut für Quantenoptik and Fakultät für Physik der Ludwig-Maximilians Universität, Munchen, Germany
3. Lebedev Institute of Physics, Moscow, Russia
**chisholm@physics.harvard.edu*

We report on recent progress of room-temperature electron spin sensing for biological applications using nitrogen-vacancy (NV) centers in diamond. Room-temperature detection of a small number of electron spins, situated outside the measurement substrate, has yet to be accomplished. Such an advance could lead to a number of applications, including measurement of concentrations of radicals in living cells, detection of magnetic resonance signals from individual electron or nuclear spins of complex biological molecules, and monitoring the ion channel function across cell membranes (important for exploring drug delivery mechanisms). Thus, the ability to measure magnetic fields with sensitivity allowing detection of a small number of electron spins with sub-micrometer resolution would be of major importance to the biological sciences.

In situ tomography of femtosecond optical beams with a holographic knife-edge

J. Strohaber[1], G. Kaya[1], N. Kaya[1], N. Hart[1], A. A. Kolomenskii[1], G. G. Paulus[1,2], and H. A. Schuessler[1]

1. Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA
2. Institut für Optik und Quantenelektronik Max-Wien-Platz 1, 07743 Jena, Germany
**jstroha1@physics.tamu.edu*

We present an in situ beam characterization technique to analyze femtosecond optical beams in a folded version of a 2f-2f setup [1]. This technique makes use of a two-dimensional spatial light modulator (SLM) to holographically redirect radiation between different diffraction orders. This manipulation of light between diffraction orders is carried out locally within the beam. Because SLMs can withstand intensities of up to $I \sim 10^{11}$ W/cm^2, this makes them suitable for amplified femtosecond radiation. The flexibility of the SLM was demonstrated by producing a diverse assortment of "soft apertures" that are mechanically difficult or impossible to reproduce. We test our method by holographically knife-edging and tomographically reconstructing both continuous wave and broadband radiation in transverse optical modes. This work was supported by the Robert A. Welch Foundation (grant No. A1546) and the National Science Foundation (grant No. 0722800).

Reference

[1] J. Strohaber, et. al., "In situ tomography of femtosecond optical beams with a holographic knife-edge," Optics Express **19,** 14321-14334 (2011).

Intensity-resolved above threshold ionization yields obtained with femtosecond laser pulses

N. Hart[1], J. Strohaber[1], G. Kaya[1], A. A. Kolomenskii[1], G. G. Paulus[2], and H. A. Schuessler[1,*]

1. Department of Physics and Astronomy, College Station ,Tx 77843-4242
2. Institut für Optik und Quantenelektronik Max-Wien-Platz 1, 07743 Jena, Germany
**schuessler@physics.tamu.edu*

Photoelectron yields from the ionization of xenon with linearly polarized, unchirped 50 fs laser pulses were measured for a set of laser intensities using an above threshold ionization (ATI) [1] apparatus. All laser parameters other than the radiation intensity were held constant over the set of intensity measurements. A recently developed deconvolution algorithm was used to retrieve the photoelectron ionization probability from spatially averaged data in three dimension. Finally, an error analysis was performed to determine the stability and accuracy of the algorithm as well as the quality of the data. It was found that the algorithm produced greater contrast for peaks in the ATI spectra where atom specific resonant behavior is observed. Additionally, the total yield probability showed that double ionization was observed in the ionization yields. The error analysis revealed that the algorithm was stable under the experimental conditions for a range of intensities. This work was supported by the Robert A. Welch Foundation (grant No. A1546) and the National Science Foundation (grant No. 0722800) and the U.S. Army Research Office (W911NF-07-1-0475).

Reference

[1] G. G. Paulus, W. Nicklich, Huale Xu, P. Lambropoulos, and H. Walther, "Plateau in above threshold ionization spectra", Phys. Rev. Lett. 72, 2851–2854 (1994).

Time evolution method in rigged QED: formulation and simulation

Kazuhide Ichikawa, Masahiro Fukuda, and Akitomo Tachibana*

Department of Micro Engineering, Kyoto University, Kyoto 606-8501, Japan
**akitomo@scl.kyoto-u.ac.jp*

Simulations of time evolution of the quantum system involving light and matter are so far performed using the time-dependent Schrödinger or Dirac equation with classical electromagnetic fields or using a quantized photon field with the very much simplified matter part. We consider, however, it is of great importance to develop a simulation method based on QED (Quantum Electrodynamics) in the form of quantum field theory, and without recourse to the perturbative approach. We believe such a theoretical technique opens up a way to study and predict new phenomena. Rigged QED [1] is a theory which has been proposed to treat dynamics of charged particles and photons in atomic and molecular systems in a quantum field theoretic way. We discusses a method to follow the step-by-step time evolution of the quantum system employing Rigged QED. We found "electron-positron oscillations" in the charge density, the fluctuations originated from virtual electron-positron pair creations/annihilations [2].

References

[1] A. Tachibana, J. Chem. Phys. **115**, 3497 (2001); J. Mol. Struct. (THEOCHEM), **943**, 138 (2010).
[2] K. Ichikawa, M. Fukuda and A. Tachibana, International Journal of Quantum Chemistry, published online. [DOI: 10.1002/qua.24087].

Strong-field above-threshold ionization in laser-irradiated C_{60}: the signature of orbital symmetry and intramolecular interference

Vladimir Usachenko[1,2,*], Pavel Pyak[2], and Vyacheslav Kim[3]

1. Institute of Applied Physics, National University of Uzbekistan, Tashkent, Uzbekistan
2. Physics Department, National University of Uzbekistan, Tashkent, Uzbekistan
3. Institute of Ion-Plasma and Laser Technologies, Tashkent, Uzbekistan
**vusach@yahoo.com*

The strong-field process of multiphoton *above-threshold ionization* (ATI) in laser-irradiated carbon molecule of fullerene C_{60} is addressed theoretically within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA) [1]. Our VG-SFA results demonstrate a high suppression of ATI peaks in two different (viz., in low-energy and high-energy) domains of calculated molecular photoelectron spectrum and two respective pronounced interference minima both arising due to destructive *intramolecular* (multislit) quantum interference. The applied approach also suggests quite a clear and transparent interpretation for the physical mechanism underlying the phenomenon of high suppression in C_{60} strong-field ionization earlier observed in relevant experiment [2].

References

[1] Vladimir I. Usachenko, Pavel E. Pyak and Vyacheslav V. Kim. "Comparative study of strong-field ionization in laser-irradiated F_2 and other diatomic molecules: Density-functional-theory-based molecular strong-field approximation", Phys. Rev. A **79**, p. 023415 (2009).
[2] M. Tchaplyguine *et al.* "Ionization and fragmentation of C_{60} with sub-50 fs laser pulses", J. Chem. Phys. **112**, pp. 2781-2789 (2000).

Generation of a pilot phase pulse during propagation of slow elliptically polarized optical pulses in a medium under coherent population trapping

M. Yu. Basalaev[1,2], D. V. Brazhnikov[2,3,*], A. V. Taichenachev[2,3], A. M. Tumaikin[3], and V. I. Yudin[1,2,3]

1. Novosibirsk State Technical University, Novosibirsk, Russia
2. Novosibirsk State University, Novosibirsk, Russia
3. Institute of Laser Physics SB RAS, Novosibirsk, Russia
**LLF@laser.nsc.ru*

Propagation of elliptically polarized light pulses under the coherent population trapping (CPT) in a medium of two-level atoms with degenerate energy levels is studied. Theoretical analysis is based on the density matrix formalism and the reduced Maxwell's equation. It is shown that the pulses of ellipticity and orientation angle of the polarization ellipse travel with delay. We derive the analytical expression for a group velocity for all possible "dark" transitions $J_g = J \rightarrow J_e = J$ (J is integer), where J_g and J_e are the total angular momentum of atomic ground and excited states. In addition, the new interesting effect is revealed. The sense of the effect consists in stimulated phase modulation due to variation of the polarization ellipse spatial orientation. This phase modulation includes two light pulses: a pilot pulse that passes through the medium with velocity of light in vacuum and a slow pulse, propagating in sync with the pulse of the orientation angle.

Numerical study on the spin coherence in a non-ideal atom cloud

Chia Zhong Yi[1] and David Wilkowski[1,2,3]

1. Centre for Quantum Technologies, National University of Singapore, Singapore
2. Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore
3. INLN, Université de Nice Sophia Antipolis, France
**contact.forthispaper@whereareyoufrom.com*

The robustness of cohenrent nuclear spin superposition was to be tested experimentally under electromagnetically-induced transparency scheme [1] using a Λ-system consisted of Sr^{87} atoms in $|^1S_0, F=9/2, m_F=5/2\rangle$, $|^1S_0, F=9/2, m_F=9/2\rangle$, $|^3P_1, F=7/2, m_F=7/2\rangle$ states. The storage time of light in a coherent spin superposition was planned to be measured in the experiment. A numerical semi-classical approach to solve the distribution of atoms [2] under the previous set-up was performed so as to provide an insight to the situation where a minority of 'impurity' Sr^{87} atoms in different spin states existed, resulting in low temperature collisions in the cloud. Such impact in spin coherence of the atom cloud was to be investigated through the simulation.

References

[1] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, "Storage of light in atomic vapor," Phys. Rev. Lett., vol. 86, p. 783, 2001.
[2] T. Lepers, D. Davesne, S. Chiaccheira, and M. Urban, "Numerical solution of the Boltzmann equation for the collective modes of trapped Fermi gases," Phys. Rev. A., vol. 82, p. 023609, 2010.

Dynamical decoherence control of atomic spin ensemble

Kallol Roy[1,*], Biswajit Das[2], R. Srikanth[3], Bimalendu Deb[2], and T. Srinivas[1]

1. Applied Photonics lab, Indian Institute of Science, Bangalore, India
2. Department of Materials Science, Indian Association for the Cultivation of Science, Kolkata, India
3. Poornaprajna Institute of Scientific Research, Bangalore, India
**kallol@ece.iisc.ernet.in*

Decoherence of central spin S in a bath made of sufficiently close I spins leads to loss quantum property of central spin. The coupling between different central spins S and intrabath coupling is neglected. We apply spin flip σ_i at time t_i and $\mathcal{G} = \{\sigma_i\}$. We use controlled randomness in dynamical decoupling for switching off unwanted evolution in interacting quantum systems by proposing a random decoupling setting that uses a random decoupler to encode a logical frame related to physical of and then to spin flip the system randomly over time by following a random control path.

Reference

[1] V. V. Dobrovitski, A. E. Feiguin, D. D. Awschalom, and R. Hanson, *Decoherence Dynamics of single spin versus spin ensemble*, Phys. Rev. B **77**, 245212 (2008).

Quantum particles around near-black hole objects: resonant particle capture, spectrum collapse, and the smooth transition to black hole absorption

Julian Berengut[1], Victor Flambaum[1], G. H. Gossel[1], and G. F. Gribakin[2]

1. School of Physics, University of New South Wales, Sydney NSW 2052, Australia
2. School of Mathematics and Physics, Queens University, Belfast BT7 1NN, Northern Ireland, UK

We investigate quantum properties of particles in the gravitational fields of “near black-hole objects”: bodi es with radius R that slightly exceeds the Schwarzschild radius r_s. We find that massless quantum particles scattered by the gravitational field of such an object possess a dense spectrum of narrow resonances: a set of long lived metastable states whose lifetimes and density tend to infinity in the black-hole limit $R \to r_s$. The cross-section of particle capture into these resonances at low energy is equal to the absorption cross-section for a Schwarzschild black hole; thus, a non-singular static metric acquires black-hole properties before the actual formation of a black hole [1]. Massive particles also have bound states in the field of these near black-hole objects. In the limit $R \to r_s$ all bound states tend to zero energy and the energy spectrum becomes quasi-continuous. However until there is a singularity in the metric, there are no zero-energy states, and hence no pair production occurs in these systems.

References

[1] V. V. Flambaum, G. H. Gossel, and G. F. Gribakin, accepted to Phys. Rev. D (2012), arXiv:1012.2134.
[2] G. H. Gossel, J. C. Berengut, and V. V. Flambaum, Gen. Rel. Gravit., **43**, 2673 (2011).

Adiabatic evolution of light in parallel curved optical waveguide array

Hristina S. Hristova[1,2,*], Andon A. Rangelov[1], Stephan Guerin[2], and Nikolay V. Vitanov[1]

1. Department of Physics, Sofia University, James Bourchier 5 Boulevard, 1164 Sofia, Bulgaria
2. Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR CNRS 6303, Boîte Postale 47870, 21078 Dijon, France
**hristina_hristova@phys.uni-sofia.bg*

Adiabatic evolution of light in parallel curved optical waveguide array is theoretically investigated. For two waveguides it has been demonstrated in [1]. This problem is shown to bear a close connection with coherent population transfer in a "bow-tie" model for atoms and molecules. For the presented models complete light transfer between the outer waveguides is achieved, and the respective conditions of validity are given. These conditions impose certain restrictions on the geometry of the waveguides and on the optical properties of the system. The case of three waveguides is analysed using the solutions of the well known bow-tie model. For the case of more than three waveguides the system can be reduced to a number of three-level waveguide sub-systems. The latter is illustrated on the specific example of an array of four waveguides. Analytic results supported by numerics are derived for complete light transfer.

Reference

[1] F. Dreisow, A. Szameit, M. Heinrich, S. Nolte, A. Tünnermann, M. Ornigotti and S. Longhi, *Direct observation of Landau-Zener tunnelling in a curved optical waveguide coupler*, Phys. Rev. A **79**, 055802 (2009).

Circularly polarized emission from ensembles of InGaAs/GaAs quantum rings

R. Naouari[1,*], W. Ouerghui[1], J. Martinez-Pastor[2], J. Gomis[2], M. A. Maaref[1], D. Granados[3], and J. M. Garcia[3]

1. Unité de Recherche des Physiques des Semiconducteurs et Capteurs, Institut Préparatoire aux Etudes Scientifiques et Techniques Université Carthage. La Marsa 2070, Tunis, Tunisia
2. Instituto de Ciencia de los Materials, Universidad de Valencia, P. O. Box 22085, 46071 Valencia, Spain
3. Instituto de Microelectrónica de Madrid, Isaac Newton 8, 28760 Tres Cantos, Madrid, Spain
**naouari_raja@hotmail.fr*

The magnetic-field dependence of the circular polarization evidences the exciton fine structure and helps to determine the anisotropic part of the exciton exchange splitting. This splitting increases from 110 to 160 μeV with increasing the detection energy. This behavior is explained by the fact that the splitting is essentially due to the anisotropic shape in this quantum ring [1]. Symmetry of the QR structures as well as its breaking cause characteristic features in the optical spectra, which are determined by the electron –hole exchange and the Zeeman interaction of the carriers. The symmetry breaking is either inherent to the dot due to geometry asymmetries, or it can be obtained by applying a magnetic field with an orientation different from the ring axis.

Reference

[1] G., Bester *et al.*, Phys. Rev. B 67, 161306(R) (2003).

Thursday Posters

Experimental demonstration of a 12-meter atomic fountain

Lin Zhou, Biao Tang, Wencui Peng, Wei Yang, Jin Wang, and Mingsheng Zhan*

State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China
Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
**mszhan@wipm.ac.cn*

Atomic fountains with launch height less than one meter are widely used in atomic frequency standards and atom interferometers. One of the key parameters of fountain type atom interferometer is the free evolution time between Raman pulses. Longer falling time is better for improving the accuracy of an atom interferometer [1]. For this purpose, large size atomic fountain is necessary for precision measurements based on atom interferometers. We experimentally constructed a 10-meter atom interferometer, and observed the time of flight signals with different launch velocities [2]. Recent data shows that, the maximum launch velocity can be 13.91 m/s, and the corresponding fountain height exceeds 12 m and the free evolution time for fountain type atom interferometer is up to 1.50 s. The temperatures and cold atom numbers of different fountain heights were measured, and the experimental data are agreed well with theoretical expectation.

References

[1] S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, "Testing general relativity with atom interferometry", Phys. Rev. Lett., **98**, pp.111102 (2007).
[2] L. Zhou *et al.*, "Development of an atom gravimeter and status of the 10-meter atom interferometer for precision gravity measurement", Gen. Relativ. Gravit. **43**, pp.1931-1942 (2011).

Ultra-high resolution spectroscopy with atomic or molecular Dark Resonances

Thomas Zanon-Willette[1,2,*], Emeric de Clercq[3], and Ennio Arimondo[4]

1. UPMC Univ. Paris 06, UMR 7092, LPMAA, 4 place Jussieu, case 76, 75005 Paris, France
2. CNRS, UMR 7092, LPMAA, 4 place Jussieu, case 76, 75005 Paris, France
3. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 avenue de l'Observatoire, 75014 Paris, France
4. Dipartimento di Fisica "E. Fermi", Università di Pisa, Lgo. B. Pontecorvo 3, 56122 Pisa, Italy
**thomas.zanon@upmc.fr*

Exact and asymptotic lineshape expressions are derived from the semi-classical density matrix representation describing a set of closed three-level Λ atomic or molecular states including decoherences, relaxation rates and light-shifts [1]. An accurate analysis of the exact steady-state Dark Resonance profile leads to the linewidth expression of the two-photon Raman transition and frequency-shifts associated to the clock transition. From an adiabatic analysis of the dynamical Optical Bloch Equations in the weak field limit, a pumping time required to efficiently trap a large number of atoms into a coherent superposition of long-lived states is established. When time separated resonant two-photon pulses are applied in the adiabatic pulsed regime where the first pulse is long enough to reach a coherent steady-state preparation and the second pulse is very short to avoid repumping into a new dark state, Dark Resonance fringes mixing continuous-wave lineshape properties and coherent Ramsey oscillations are created. Those fringes allow interrogation schemes bypassing the power broadening effect. We point out that different observables experience different shifts on the lower-state clock transition.

Reference

[1] T. Zanon-Willette, E. de Clercq and E. Arimondo, Phys. Rev. A **84**, 062502 (2011).

Atom interferometry in an inductively coupled ring trap

Jonathan D. Pritchard*, Aline N. Dinkelaker, Aidan S. Arnold, Paul F. Griffin, and Erling Riis

Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK
**jonathan.pritchard@strath.ac.uk*

Atom interferometry offers significant benefits to the field of precision metrology due to the sensitivity to external electromagnetic fields and inertial forces, whilst permitting significantly longer interaction times compared to optical sensors. We report on experimental progress towards realising atom interferometry in a novel toriodal ring trap for ultracold atomic gases [1]. The time-averaged trapping potential is formed by applying a uniform a.c. magnetic field to induce an opposing current in a conducting ring. This resolves the issue of perturbations due to electrical connections and benefits from time averaging of corrugating potentials due to current meandering.

We present a characterisation of of the time-averaged potential for a laser cooled cloud in a 5 mm ring trap, and present the status of a second generation apparatus to use Bose (^{87}Rb) and Fermi (^{40}K) degenerate gases for Sagnac interferometry within a ring trap of radius 2 mm.

Reference

[1] P. F. Griffin, E. Riis and A. S. Arnold, *Smooth inductively coupled ring trap for atoms*, Phys. Rev. A **77**, 051402(R) (2008).

Th-004 Atom interferometry

High data-rate atom interferometer accelerometers and gyroscopes

Hayden McGuinness[1,*], Akash Rakholia[1,2], and Grant Biedermann[1,2]

1. Sandia National Laboratory, Albuquerque, USA
2. Center for Quantum Information and Control, Dept. of Physics and Astronomy/University of NewMexico, Albuquerque, USA
**hmcgui@sandia.gov*

Atom interferometer (AI) accelerometers and gyroscopes are poised to significantly advance applications in inertial navigation, seismic studies, gravimeter surveys, and tests of fundamental physics. A key advantage of AI systems over competing technologies is their inherent capability for long-term stability and intrinsic calibration. However, in their current form, AI systems are ill-suited to complement or replace the leading technologies in the more dynamic of these applications due to their relatively large size and low operating rates, which are on the order of one Hertz.

We demonstrate a compact AI accelerometer operating at rates between 50 and 330 Hertz, roughly two orders of magnitude higher than any other published AI accelerometer, achieving sensitivities on the order of $\mu g/\sqrt{\text{Hz}}$ [1]. This operating rate, sensor size, and sensitivity level open the door for AI systems to be considered suitable for applications in highly dynamic environments. We are currently working towards a dual accelerometer/gyroscope AI system, allowing simultaneous acceleration and rotation measurements, which is projected to have operating rates and sensitivities suitable for dynamic environments.

Reference

[1] H. J. McGuinness, A. V. Rakholia, and G. W. Biedermann, "High data-rate atom interferometer for measuring acceleration", Appl. Phys. Lett. 100, 011106 (2012).

A clock referenced to a particle's mass; defining the kilogram in terms of the second

Shau-Yu Lan[1,*], Pei-Chen Kuan[1], Brian Estey[1], Damon English[1], Justin M. Brown[1], Michael A. Hohensee[1], and Holger Müller[1,2]

1. Department of Physics, 366 Le Conte Hall MS7300, University of California, Berkeley, California 94720, USA
2. Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, California 74720, USA
**sylan@berkeley.edu*

What is the simplest system that can mark the passage of time? Massless particles move at the speed of light, c and thus do not experience time. A single particle with nonzero rest mass m_0, however, can. Relativity and quantum mechanics relate its mass, energy E, and the reduced Planck constant $\hbar$ as $E=m_0c^2=\hbar\omega_0$. This formally defines a Compton frequency ω_0 [1], but it has never been directly demonstrated that Compton frequency oscillations are physically meaningful - *e.g.*, by using them as the basis for a clock. Combining an atom interferometer and a frequency comb, here we present a clock stabilized to a fraction of Compton frequency. By measuring the Compton frequency of an atom, our experiment measures its mass, and makes possible a quantum definition of the kilogram. This could be used to produce a macroscopic mass standard of superior accuracy and repeatability which is directly linked to the second by assigning a fixed value to $\hbar$.

Reference
[1] De Broglie L. "Recherches sur la théorie des quanta", Ph.D. Thesis, Univ of Paris (1924).

Atom interferometry Th-006

Testing Einstein's equivalence principle with a lithium interferometer

Paul Hamilton[1,*], Geena Kim[1], Marcus Ossiander[2], Biswaroop Mukharjee[1], Daniel Tiarks[3], and Holger Müller[1]

1. University of California, Berkeley, CA, USA
2. Max-Planck-Institute of Quantum Optics, Garching, Germany
3. Institut fuer Quantenoptik, Leibniz Universitaet Hannover
**paul.hamilton@berkeley.edu*

Measurements of the acceleration due to gravity for bodies of differing composition have long been used to test Einstein's equivalence principle underlying general relativity. A ^{6}Li-^{7}Li matter wave interferometer test of EEP would have high sensitivity to new physics because of the relatively large difference between ^{6,7}Li nuclei [1]. An optical lattice will be loaded from a dual species 2D/3D-magneto-optical trap. The lattice will then be employed both as a waveguide to prevent atom losses due to the high thermal velocity of Li, and as large momentum transfer beam splitters in analogy to the Bloch-Bragg-Bloch beam splitters developed by us [2]. We anticipate an accuracy of 10^{-14} g for the differential acceleration measurement. We discuss investigations of novel all-optical sub-doppler cooling of lithium as well as progress towards a demonstration of the first ultracold lithium interferometer.

References
[1] M. Hohensee *et al.*, "Equivalence Principle and Gravitational Redshift", Phys. Rev. Lett. **151102** (2011).
[2] H. Müller *et al.*, "Atom Interferometers with Scalable Enclosed Area", Phys. Rev. Lett. **240403** (2009).

A tunable ^{39}K BEC for atom interferometry

Manuele Landini[1,2,*], Sanjukta Roy Chaudhuri[2], Andreas Trenkwalder[1], Giovanni Modugno[1,2,3], Massimo Inguscio[1,2,3], and Marco Fattori[1,2,3]

1. INO-CNR, Sesto Fiorentino, Italy
2. LENS, Universtà degli studi di Firenze, Sesto Fiorentino, Italy
3. INFN, Sezione di Firenze, Sesto Fiorentino, Italy
**landini@lens.unifi.it*

We present our recent progresses towards the realization of an atomic double well interferometer employing a Bose-Einstein condensate of ^{39}K with tunable interactions. The tunability of interactions, guaranteed by several wide Feshbach resonances available for this particular atomic species, will enable us to create squeezed states to be fed at the interferometer input as well as to operate the interferometer in absence of interactions. The former ability will allow us to reach sub-shot noise resolutions and the latter to avoid interaction induced decoherence. We achieved condensation of ^{39}K for the first time without the help of any coolant thanks to the recent demonstration of sub-Doppler cooling for this species [1] and the employment of Feshbach assisted evaporation in an optical dipole trap. Pure condensates containing up to 8×10^5 potassium atoms can be prepared in less than 20 seconds in a science chamber with large optical access. The double well is under development and will be realized by employing an optical superlattice generated by the interference of two pair of bichromatic beams with 1064 and 532 nm wavelengths.

Reference

[1] M. Landini, S. Roy, L. Carcagnì, D. Trypogeorgos, M. Fattori, M. Inguscio, and G. Modugno,”Sub-Doppler laser cooling of potassium atoms”, Phys. Rev. A, 84, 043432 (2011).

Observation of free-space single-atom matterwave interference

L. P. Parazzoli[1], A. M. Hankin[1,2], and G. W. Biedermann[1,2,*]

1. Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
2. Center for Quantum Information and Control (CQuIC), Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA
**gbieder@sandia.gov*

We observe matterwave interference of a single cesium atom in free fall. The interferometer is an absolute sensor of acceleration and we show that this technique is sensitive to forces at the level of 3.2×10^{-27} Newtons with a spatial resolutionat the micron scale. We observe the build up of the interference pattern one atom at a time in an interferometer where the mean path separation extends far beyond the coherence length of the atom. Using the coherence length of the atom wavepacket as a metric, we directly probe the velocity distribution and measure the temperature in 1-D of a single atom in free fall.

Local gravity measurement with the combination of atom interferometry and Bloch oscillations

Renée Charrière[1], Malo Cadoret[2], Nassim Zahzam[1], Yannick Bidel[1,*], and Alexandre Bresson[1]

1. ONERA, Palaiseau, France
2. Laboratoire Commun de Métrologie LNE-CNAM, La plaine Saint Denis, France
**yannick.bidel@onera.fr*

Gravimeters based on atom interferometry have shown impressive results (sensitivity ~ 10^{-8} g.Hz$^{-1/2}$) but need a falling distance of at least 7 cm, preventing them from being miniaturized and making local gravity measurement. Atomic gravimeters based on Bloch oscillations or based on suspension of atoms using optical pulses can measure gravity with an interaction distance of a few micrometers but the performance (sensitivity ~ 10^{-7} g in one hour) is reduced compared to gravimeters based on atom interferometry.

We present an atom gravimeter combining atom interferometry and Bloch oscillations. This scheme allows us to associate the sensitivity provided by atom interferometry and the locality provided by Bloch oscillations. With a falling distance of 0.8 mm, we achieve a sensitivity of 2×10^{-7} g with an integration time of 300 s. No bias associated with the Bloch oscillations has been measured. A contrast decay with Bloch oscillations has been observed and attributed to the spatial quality of the laser beams. A simple experimental configuration has been adopted where a single retroreflected laser beam performs atom launches, stimulated Raman transitions, and Bloch oscillations.

Kapitza-Dirac diffraction with quantum prepared initial states for two-bunch atom interferometry

Lilit Hovhannisyan and Gevorg Muradyan*

Department of Physics, Yerevan State Univeristy, Yerevan, Armenia
**gmurad@ysu.am*

The problem of resonant Kapitza – Dirac diffraction is discussed in Raman – Nath approximation out of familiar Bessel function approximation (applicable for zero and large resonance detuning cases). We show that in case when the initial atomic momentum state is prepared in a form of discrete Gaussian distribution, instead of a monotonic broadening within the Bessel function approximation, the initial distribution splits into two identical peaks. These peaks, keeping their form, symmetrically move away from the distribution center during interaction time. We also discuss conditions under which is possible to obtain a table-shaped form for momentum distribution, which is a strongly recommended distribution in high resolution spectroscopy in optics.

Detection of the He-McKellar-Wilkens geometric phase by atom interferometry

S. Lepoutre, J. Gillot, A. Gauguet, G. Trénec, M. Büchner*, and J. Vigué

Laboratoire Collisions, Agrégats, Réactivité-IRSAMC, Université de Toulouse-UPS and CNRS – UMR 5589 Toulouse, France
**matthias.buchner@irsamc.ups-tlse.fr*

We present the first experimental detection of a geometric phase, predicted by He and McKellar and by Wilkens in 1993 [1]. This phase, closely related to the Aharonov-Bohm and the Aharonov-Casher phases, appears when an electric dipole **d** propagates with a velocity **v** in a magnetic field **B** and this phase is proportional to **d.(v×B)**. In order to observe this phase with an atom interferometer, we must polarize the atom using different electric fields on the two interfering paths: this is possible in our experiment because a thin electrode (a septum) can be inserted between the two interferometers arms. With our arrangement, the He-McKellar-Wilkens phase shift is small, about 20 mrad: its detection has been possible thanks to the high sensitivity of our atom interferometer, to a new data recording procedure cancelling phase drifts and to a detailed analysis of stray phases. The measured value is in good agreement with theory [2].

References

[1] X.-G. He and B. H. J. McKellar, Phys. Rev. A 47, 3424 (1993).
M. Wilkens, Phys. Rev. Lett. 72, 5 (1994).
[2] S. Lepoutre, A. Gauguet, G. Trénec, M. Büchner, and J. Vigué, submitted to Phys. Rev. Letters.

Atom interferometry with an optically pumped lithium beam

J. Gillot, S. Lepoutre, A. Gauguet, G. Trénec, M. Büchner*, and J. Vigué

Laboratoire Collisions, Agrégats, Réactivité-IRSAMC, Université de Toulouse-UPS and CNRS – UMR 5589 Toulouse, France
**matthias.buchner@irsamc.ups-tlse.fr*

The He-McKellar-Wilkens (HMW) topological phase [1] appears when an electric dipole travels though a magnetic field and its detection requires an atom interferometer with separated paths [2]. In such a high precision atom interferometry experiment, a weak gradient of the magnetic field induces spurious phases, which are difficult to interpret because the signal is the sum of the contribution of all the magnetic sub-levels of the atom ground state but we can simplify considerably the interpretation of the experiments by pumping the lithium beam in a single F,m_F sub-level. We have chosen to pump the atoms in the $F=2$, $m_F=+2$ (or -2) sub-level by using two lasers on components of the D_1 line. We have characterized the pumped beam by optical spectroscopy and by an interferometric method. In this last case, a magnetic field gradient is applied on the interferometer arms and the fringe visibility and phase shift are measured as a function of the applied gradient: the observed variations are connected to the atom distribution over the F,m_F sub-levels. We will present our experimental results and we will discuss the use of the pumped beam for a new measurement of the HMW phase.

References

[1] X.-G. He and B. H. J. McKellar, Phys. Rev. A **47**, 3424 (1993); . Wilkens, Phys. Rev. Lett. **72**, 5 (1994).
[2] S. Lepoutre, A. Gauguet, G. Trénec, M. Büchner, and J. Vigué, submitted to Phys. Rev. Letters.

Clock laser system for a new implementation of the indium-ion optical clock

Y. Li*, C. R. Locke, S. Nagano, K. Matsubara, Y. Hanado, and K. Hayasaka

National Institute of Information and Communications Technology, Koganei, Tokyo 184-8795, Japan
**liying@nict.go.jp*

Exceptional fractional frequency uncertainty of parts in 10^{-18} has been reported using $^{27}Al^{+}$ in a single-ion optical clock [1]. Here we investigate another promising ion candidate; indium ($^{115}In^{+}$) which, like $^{27}Al^{+}$, has small blackbody radiation shift compared to other neutral and ionic clock candidates. Although current techniques using indium have been unable to reach this level of performance, recently proposed new implementations [2] indicate this exceptionally low uncertainty is attainable. This new approach sympathetically cools an indium ion using laser-cooled Ca^{+} ions, and detects the clock transition by electron shelving using CW light at the $^1S_0$-$^3P_1$ transition (230nm, 360kHz), or using the $^1S_0$-$^1P_1$ transition (159nm, ~200MHz) by pulses prepared by high harmonic generation. Of critical importance is the 237nm clock laser, which must be stable in frequency for over 100 seconds during the long diagnosis period. We report details of the 237nm radiation generated by two-stage frequency doubling of an amplified extended-cavity diode laser at 946nm locked to a rectangular ULE cavity of length 150mm and having low sensitivity to vibration.

References

[1] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, T. Rosenband, Phy. Rev. Lett. 104, 070802 (2010).
[2] K. Hayasaka, Appl. Phys. B. Doi: 10.1007/s00340-012-4909-9 (2012).

Atomic clocks Th-014

Towards a laser at 729 nm with hertz-level linewidth

Gaetan Hagel, Olivier Morizot, Caroline Champenois, Didier Guyomarc'h, Marie Houssin, Jofre Pedregosa, and Martina Knoop

Physique des Interactions Ioniques et Moléculaires, Université d'Aix-Marseille, CNRS, Centre Universitaire de St. Jerome – Case C21, 13397, Marseille, France

We report progression in the reduction of the linewidth of a lab-built Ti Sa laser at 729 nm, with the goal to realize an atomic frequency standard at this wavelength by locking a local oscillator on a forbidden transition in an rf trapped calcium ion. Recent results have been obtained by using the Pound-Drever-Hall technique to lock the frequency of this laser radiation on the fringe of an ultra-stable Fabry-Perot cavity [1] with a finesse superior to 140.000. In order to assure short- and mean-term frequency stability this cavity has to be maximally decoupled from its environment by several stages of vibrational and thermal isolation. The fast linewidth of the laser radiation is estimated from the recorded error-signal with respect to the reference cavity. Future steps will also be presented.

Reference

[1] D. Guyomarc'h *et al.*, "Some aspects of simulation and realization of an optical reference cavity", Phys. Rev. A 80, 063802 (2009).

Experiments on optical lattices for ytterbium optical clocks

Min Zhou, Ning Chen, Xiaohang Zhan, Liangyu Huang, Maofei Yao,
Jie Tian, Qi Gao, Hailing Jiang, Haiyao Tang, and Xinye Xu*

State Key Laboratory of Precision Spectroscopy and Department of Physics,
East China Normal University, Shanghai 200062, China
**xyxu@phy.ecnu.edu.cn*

We have done experiments on laser cooling and trapping of ytterbium atoms for developing an ytterbium optical clock. The experimental setup includes lasers with wavelengths of 399 nm for the first-stage cooling, 556 nm for the second-stage cooling and 759nm for an optical lattice. The temperature and number of cold ^{171}Yb atoms in 399-nm MOT were 2 mK and 10^7 respectively. After one second, we turned off the 399-nm MOT and simultaneously turned on the 556-nm MOT. By optimizing the various experimental parameters, we can load the 50% atoms from the 399-nm MOT into the 556-nm MOT. MOT. The temperature of ^{171}Yb atoms is about 10 μK with 10^6 atoms. Finally, we have successfully loaded the cold ^{171}Yb atoms into an optical lattice with a wavelength of 759 nm. The lifetime and temperature of atoms in the optical lattice are measured. Now we are going to observe the $^1S_0 - {}^3P_0$ clock transition by using the ultra narrow laser, developing an ytterbium optical clock.

References

[1] M. Takamoto, F. Hong, R. Higashi, and H. Katori, Nature **435**, 321-323 (2005).
[2] A. D. Ludlow *et al.*, Science **319**, 1805-1807 (2008).
[3] Z. W. Barber *et al.*, Phys. Rev. Lett. **96**, 083002 (2006).
[4] H. Jiang, G. Li and X. Xu, Optics Express, **17**, 16073-16080 (2009).

Spin waves and collisional frequency shifts of trapped-atom clocks

W. Maineult[1], C. Deutsch[2], K. Gibble[3], J. Reichel[2], and P. Rosenbusch[1,*]

1. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, France
2. LKB, Ecole Normale Supérieure, CNRS, UPMC, France
3. The Pennsylvania State University, USA
**Peter.Rosenbusch@obspm.fr*

We simulate the collisional frequency shift of optical lattice clocks based on fermions using a trapped atom clock on a chip [1]. At ultra-low temperatures, Pauli exclusion forbids collisions of identical fermions, making fermions ideal candidates for future atomic clocks and other precision measurements. But, s-wave interaction can occur when excitation fields are inhomogeneous. We observe for the first time a novel dependence of the transition frequency on the area of the 2nd pulse in Ramsey spectroscopy. We show that the fermion clock shift is inextricably linked to spin waves – whenever there is a fermion clock shift, spin wave are excited. We study the hyperfine transition of magnetically trapped 87Rb, which simulates fermions because all of its scattering lengths are nearly equal.

Reference

[1] C. Deutsch, F. Ramirez-Martinez, C. Lacroûte, F. Reinhard, T. Schneider, J. N. Fuchs, F. Piéchon, F. Laloë, J. Reichel, and P. Rosenbusch "Spin Self-Rephasing and Very Long Coherence Times in a Trapped Atomic Ensemble" Phys. Rev. Lett. **105**, 020401 (2010).

Evaluation of the dynamic correction to the black-body radiation clock shift in Yb

N. Hinkley[1,2], N. D. Lemke[1,2], A. D. Ludlow[1], J. A. Sherman[1], K. Beloy[1,*], C. W. Oates[1], and A. Derevianko[3]

1. National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA
2. University of Colorado, Department of Physics, Boulder, Colorado 80309, USA
3. Department of Physics, University of Nevada, Reno, Nevada 89557, USA
**kyle.beloy@nist.gov*

We evaluate the dynamic correction to the black-body radiation (BBR) shift of the $6s^2\,{}^1S_0 \rightarrow 6s6p\,{}^3P_0^\circ$ optical clock transition in Yb. This complements recent work in our laboratory which accurately characterized the BBR clock shift within the "static" approximation—i.e., wherein subtle effects of the spectral distribution of the thermal radiation are neglected. En route to this result, we identify a standing 3σ theory-experiment disagreement for the $6s6p\,{}^3P_0^\circ - 5d6s\,{}^3D_1$ electric dipole matrix element, which plays a key role in the dynamic correction. This discrepancy has prompted us to independently determine this matrix element by two separate means. Firstly, we extract the matrix element by utilizing a combination of accurate experimental parameters including the magic wavelength and the static Stark coefficient associated with the clock transition. Secondly, we perform a measurement of the $5d6s\,{}^3D_1$ radiative lifetime with Yb atoms confined in an optical lattice. Our results for this matrix element obtained by these two methods are in agreement with one another, and largely validate the prior theoretical value. With this matrix element, we are able to determine the fractional clock shift to well below 1×10^{-17} for operation in a BBR environment at 300 K.

Atomic clocks Th-018

Comparison of two state-of-the-art Strontium optical lattice clocks

Jérôme Lodewyck[1,*], Bartłomiej Nagórny[2], Luca Lorini[3], Mikhail Gurov[1], Pierre Lemonde[1], and Rodolphe Le Targat[1]

1. LNE SYRTE, Observatoire de Paris, Paris, France
2. Institute of Physics, Nicolaus Copernicus University, Toruń, Poland
3. Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
**jerome.lodewyck@obspm.fr*

For the first time, two state-of-the-art optical lattice clocks are compared, this is the final step necessary to demonstrate that this new generation of frequency standards is now fully reliable and lives up to expectations. We present the preliminary results showing a good agreement between our two Strontium clocks within their accuracy budget (1.4×10^{-16}).

In particular, we present in-depth studies of the trapping effects. First the calibration of the residual first order light shift [1] is detailed. Secondly, we report on the second order lattice effects, observed with an unprecedented resolution due to the high depth of our lattices (5000 recoils).

Finally, we compared the strontium clocks to 3 microwave fountains, thus giving the clock transition absolute frequency to an accuracy of 4×10^{-16} limited by the fountains. These measurements improve also by a factor 10 the bounds on the variation of fundamental constants given by Sr vs Cs comparisons.

Reference

[1] P. G. Westergaard and J. Lodewyck and L. Lorini and A. Lecallier and E. A. Burt and M. Zawada and J. Millo and P. Lemonde, *Lattice-Induced Frequency Shifts in Sr Optical Lattice Clocks at the 10^{-17} Level*, Phys. Rev. Lett. **106**, pp. 210801 (2011).

Development of cesium atomic fountains at NMIJ

A. Takamizawa*, S. Yanagimachi, T. Tanabe, K. Hagimoto, and T. Ikegami

National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8563, Japan
**akifumi.takamizawa@aist.go.jp*

The recent progress in our cesium atomic fountains at National Metrology Institute of Japan (NMIJ) is presented. We have developed three fountains; NMIJ-F1, NMIJ-F2, and a truncated atomic beam fountain. NMIJ-F1 has been the primary frequency standard with uncertainty of 4×10^{-15} since 2004. So far, we have reported the data to Bureau International des Poids et Mesures (BIPM) 29 times by operating NMIJ-F1 due to the progress in the stability and the reliability of the whole system. For last one year, the operation of NMIJ-F1 has stopped due to the huge earthquake and depletion of a cesium reservoir. Currently, we are working to restart NMIJ-F1. The second fountain, NMIJ-F2, is under construction to achieve less than 1×10^{-15} in uncertainty. NMIJ-F2 has the microwave cavities which are part of the vacuum vessel [1]. Moreover, the power of cooling beams for an optical molasses reaches 100 mW per beam. In addition, we proposed the truncated atomic beam fountain to achieve both a low collisional frequency shift and high frequency stability [2].

References

[1] S. R. Jefferts, R. E. Drullinger, and A. DeMarchi, "*NIST cesium fountain microwave cavities,*" in Proceedings of the 1998 IEEE International Frequency Control Symposium, pp. 6-8 (1998).
[2] A. Takamizawa, Y. Shirakawa, S. Yanagimachi, and T. Ikegami, "Proposal of a truncated atomic beam fountain for reduction of collisional frequency shift," Phys. Rev. A **82**, 013632 (2010).

Start shift of the vibrational transition frequencies of $^{40}CaH^+$ molecular ions induced by Raman lasers

Masatoshi Kajita[1,*] and Minori Abe[2]

1. Nat.l Inst. Info. Commu. Tach,.Koganei, Tokyo, Japan
2. Tokyo Metropolitan U., Hachioji, Tokyo, Japan
**contact. for this paper kajita@nict.go.jp*

Measurement of the $X^1\Sigma$ $(v,N) = (0,0)$-> $(1,0),(2,0),(3,0),(4,0)$ transition frequencies of $^{40}CaH^+$ molecular ions in a string crystal are the promising method to test the variance in the proton-to-electron mass ratio. These molecular ions are advantageous to be produced and localized to a single (v,N,F) state, because there is no hyperfine splitting in the $N = 0$ state. The frequency uncertainty is dominated by the statistic uncertainty and the Stark shift induced by the probe laser [1]. In this paper, we consider the case that the vibrational transition is induced by Raman transition. The Stark shift with a given Rabi frequency is minimum when the power densities of two Raman lasers are equal. It is also shown that the Stark shift with the saturation power density is lowest for the $(v,N) = (0,0)$-> $(1,0)$ transition and it is much higher for overtone transitions. Considering also the statistic uncertainty, $(v,N) = (0,0)$-> $(1,0)$ transition is most advantageous for precise measurement.

Reference

[1] M. Kajita *et al.*, "Estimated accuracies of pure XH^+ (X: even isotope of group II atoms) vibrational transition frequencies: toward the test of the variance in m_p/m_e", J. Phys. B **44**, 025402 1-7 (2011).

High precision calculations of symmetry violating interactions in atoms and molecules

Nataraj S. Huliyar[1,*], Malaya K. Nayak[2], Mihály Kállay[3], Bhanu P. Das[4], and Yasuhiro Sakemi[1]

1. Cyclotron and Radioisotope Center, Tohoku University, Sendai, Japan
2. Bhabha Atomic Research Center, Trombay, Mumbai, India
3. Budapest University of Technology and Economics, Budapest, Hungary
4. Indian Institute of Astrophysics, Bangalore, India
**nataraj@cyric.tohoku.ac.jp*

It is postulated that the elementary particles such as electrons and quarks possess an intrinsic property known as the electric dipole moment (EDM), the non-zero existence of which requires a simultaneous violation of both parity and time-reversal symmetries. It implies, on assuming CPT invariance, an associated CP-violation and the latter holds an invaluable key for the understanding of the observed matter-antimatter asymmetry in the Universe. The intrinsic EDMs of these particles and their symmetry violating interactions manifest in enhancing the EDM for atoms and molecules. We have performed several high precision calculations on the EDM enhancement factors of the heavy paramagnetic atoms such as, Rb, Cs and Tl [1]. We have also developed, recently, the state-of-the-art relativistic general-order coupled-cluster program for the high precision calculations of various symmetry violating interactions in atoms and molecules. The details of the calculations together with the summary of the latest results, mainly for Fr and YbF will be presented in this conference.

Reference

[1] H. S. Nataraj, B. K. Sahoo, B. P. Das and D. Mukherjee *Reapprisal of the Electrc Dipole Moment Enhancement Factor for Thallium*, Phys. Rev. Lett. **106**, pp. 200403-200406 (2011).

Proposal for a Bell inequality test with colliding condensates

Robert Lewis-Swan* and Karen Kheruntsyan

The University of Queensland, School of Mathematics and Physics, Brisbane, QLD 4072, Australia
**robert.lewisswan@uqconnect.edu.au*

We present results of a theoretical proposal to test a Bell inequality with particles of non-zero mass. Using a pair of colliding Bose-Einstein condensates we produce correlated atoms by the process of spontaneous four-wave mixing [1]. Applying experimental tools of atom-optics, such as Bragg diffraction, we are able to create an analog of the Rarity-Tapster two-particle interferometry experiment [2] with massive particles. Analytical models and numerical simulations are found to predict a successful violation of a CHSH version of Bell's inequality in experimentally accessible parameter regimes. The violation is restricted to small occupations of the scattered modes and assumes high-efficiency atom detection.

References

[1] J. G. Rarity and P. R. Tapster, "Experimental violation of Bell's inequality based on phase and momentum", Phys. Rev. Lett. **64,** 2495, (1990).
[2] A. Perrin, C. M. Savage, D. Boiron, V. Krachmalnicoff, C. I. Westbrook and K. V. Kheruntsyan "Experimental violation of Bell's inequality based on phase and momentum", Phys. Rev. Lett. **64,** 2495, (1990).

Investigation of ac-Stark shifts in excited states of dysprosium in support of a sensitive search for temporal variations in the fine-structure constant

Christian T. M. Weber[1,2,*], Nathan Leefer[2], and Dmitry Budker[2]

1. Institut für Optik und Atomare Physik, Technische Universität Berlin, Eugene-Wigner-Bldg. EW 3-1, Hardenbergstr. 36, 10623 Berlin, Germany
2. Department of Physics, University of California at Berkeley, Berkeley, CA 94720-7300, USA
**ChristianTMWeber@gmail.com*

Throughout the past several years our group has been engaged in radio frequency spectroscopy measurements of transitions between two nearly degenerate states in dysprosium to search for changes in the fine-structure constant α [1]. Here we present measurements of ac-Stark related systematics, potentially limiting our sensitivity. We measured the reduced dipole matrix element connecting the two nearly degenerate states to be 18(2) [kHz cm/V] and the effective contribution by other states to the ac-Stark shift to 4(3) [Hz cm^2/V^2]. Along with the known energy structure we use the latter result to estimate black-body-radiation induced Stark shifts. We estimate that ac-Stark related effects contribute to systematic uncertainties below the 100 mHz level, relating to a fractional sensitivity better than $\dot{\alpha}/\alpha = 5\cdot 10^{-17}$ / yr.

Reference
[1] A. Cingöz *et al.*, *Limit on the Temporal Variation of the Fine-Structure Constant Using Atomic Dysprosium*, Phys. Rev. Lett. **98**, 040801 (2007).

Influence of angular- and spin-coupling terms on high precision calculations for lithium

Zong-Chao Yan[1,*], Liming Wang[1], and G. W. F. Drake[2]

1. Department of Physics, University of New Brunswick, Fredericton, New Brunswick, Canada
2. Department of Physics, University of Windsor, Windsor, Ontario, Canada
**zyan@unb.ca*

Improved nonrelativistic energy bounds for the low-lying states of lithium are presented using the variational method in Hylleraas coordinates. For example, the nonrelativistic energies for infinite nuclear mass are [1] – 7.478 060 323 910 147(1) a.u. for $1s^2 2s\ ^2S$, –7.354 098 421 444 37(1) a.u. for $1s^2 3s\ ^2S$, –7.318 530 845 998 91(1) a.u. for $1s^2 4s\ ^2S$, –7.410 156 532 652 4(1) a.u. for $1s^2 2p\ ^2P$, and –7.335 523 543 524 688(3) a.u. for $1s^2 3d\ ^2D$. These results represent the most accurate nonrelativistic energies in the literature. The completeness of the angular momentum and spin configurations is investigated and examples presented for the 2P and 3D states to demonstrate the effect of differentcoupling schemes. In particular, the so-called second spin function (i.e. coupled to form an intermediate triplet state) is shown to have no effect on the final converged results, even for the expectation values of spin-dependent operators such as the Fermi contact term (but not higher-order perturbations). This resolves a long-standing controversy concerning the completeness of the spin-coupling terms.

Research support by NSERC, SHARCNET, ACEnet, and the NNSF of China under Grant No. 10874133 are gratefully acknowledged.

Reference
[1] L. M. Wang *et al.*, *Variational Energies and the Fermi Contact Term for the Low-lying States of Lithium: Basis Set Completeness*, Phys. Rev. A **85**, 052513 (2012).

Observation of the nuclear magnetic octupole moment of ^{173}Yb from precise measurements of hyperfine structure in the $^3P_2$ state

Alok K. Singh* and Vasant Natarajan

Department of Physics, Indian Institute of Science, Bangalore 560012, India
**alokphy@physics.iisc.ernet.in*

Observation of the nuclear magnetic octupole moment and its influence on the hyperfine structure of atoms has remained largely unexplored because of its weaker effect compared to the leading magnetic dipole and electric quadrupole moments. However, the long lived $^3P_2$ state in atoms such as Yb and several alkaline-earth metals, with its large angular momentum, is a potentially useful probe to observe this moment [1]. We use dipole-allowed transitions to pump atoms into the metastable $^3P_2$, and then measure the absolute frequencies of various hyperfine transitions on the $^3P_2 \rightarrow {}^3S_1$ line. We measure the frequencies with our well-developed technique of using a Rb-stabilized ring-cavity resonator [2]. We obtain the hyperfine structure constants A (magnetic dipole) and B (electric quadrupole) with two orders-of-magnitude better precision than previous values, and a 10% measurement of the magnetic octupole constant C and this is the first observation of the magnetic octupole moment in this atom.

References
[1] Beloy K., Derevianko A. and Johnson W. R., *Hyperfine structure of the metastable $^3P_2$ state of alkaline-earth-metal atoms as an accurate probe of nuclear magnetic octupole moments*, Phys. Rev. A **77**, 012512 (2008).
[2] Banerjee A, Das D and Natarajan V, *Precise frequency measurements of atomic transitions by use of a Rb-stabilized resonator*, Opt. Lett. **28**, pp. 1579-81 (2003).

High resolution spectroscopy of 1S-3S transition in hydrogen

Sandrine Galtier[1], Pierre Cladé[1], Saïda Khelifa-Guellati[2], François Nez[1], Lucile Julien[1], and F. Biraben[1]

1. Laboratoire Kastler Brossel, 4 place Jussieu, case 74, 75252 Paris Cedex 05, France
2. Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75141 Paris Cedex 03, France
**galtier@spectro.jussieu.fr*

The aim of our experiment is a new determination of the proton charge radius R_p from high precision hydrogen measurements. The proton is the simplest stable hadronic system and a precise knowledge of its properties has fundamental interests. Today the proton charge radius is determined by three different methods: low energy electron scattering (R_p = 0.895 (18) fm), hydrogen spectroscopy (R_p = 0.8760 (78) fm) and muonic hydrogen spectroscopy (R_p = 0.84184 (67) fm).

There is a clear discrepancy between the new value deduced from the muonic hydrogen spectroscopy and the previous ones. The aim of our project is to measure the absolute optical frequencies of two transitions in hydrogen, firstly the 1S-3S two photon transition [1] and, secondly, the 1S-4S two photon transition. For that, a new laser source at 205 nm is developed at LKB. This radiation is generated by sum frequency. We are developing two separate ring cavities (at 894nm and 266nm) whose optical paths overlap in a Brewster-cut BBO crystal. The objective is to obtain 1 to 2 mW at 205 nm ($1/896 + 1/266 \rightarrow 1/205$). I will present the latest development of the experiment.

Reference
[1] O. Arnoult, F. Nez, L. Julien and F. Biraben, “Optical frequency measurement of the 1S-3S two-photon transition in hydrogen”, Eur. Phys. J. D **60** (2010) 243.

Slow and intense beams of YbF molecules

N. E. Bulleid[1], S. M. Skoff[1], R. J. Hendricks[1], M. R. Tarbutt[1], B. E. Sauer[1], S. A. Meek[2], G. Meijer[2], A. Osterwalder[3], D. M. Segal[1], and E. A. Hinds[1]

1. Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London, SW7 2AZ, UK
2. Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany
3. Ecole Polytechnique Federale de Lausanne, Institut des Sciences de Ingenierie Chimiques, 1015 Lausanne, Switzerland

Slow-moving, intense beams of YbF molecules have been created using buffer gas cooling and Stark deceleration. In the buffer gas method hot molecules produced by laser ablation of a solid target thermalise with cold helium buffer gas to a temperature of 4K. To make a beam, a flow of buffer gas is used so that as the molecules thermalise they are also entrained in the flow. This method has been used to create pulsed beams of YbF containing 10^{10} molecules per steradian per pulse with a rotational temperature of 4K and a forward velocity of 200m/s. Further slowing of the YbF beam can be achieved with Stark deceleration. In a travelling wave decelerator an electric field contains the YbF molecules in a trap which travels with a velocity equal to the beam. The trap is then decelerated to reduce the final velocity of the beam. We have used this in combination with a cryogenic pulsed gas source to decelerate a beam of YbF from 300m/s to 276m/s [1].

Reference

[1] N. E. Bulleid, R. J. Hendricks, E. A. Hinds, S. A. Meek, G. Meijer, A. Osterwalder and M. R. Tarbutt, *Traveling wave deceleration of heavy polar molecules in low-field seeking states*, arXiv:1204.5877v1.

Improved measurement of the electron electric dipole moment using YbF

I. J. Smallman*, J. J. Hudson, J. A. Devlin, M. R. Tarbutt, B. E. Sauer, E. A. Hinds

Centre For Cold Matter, The Blackett Laboratory, Prince Consort Rd, London, SW7 2BW, UK
**joe.smallman09@imperial.ac.uk*

It is well known that the existence of an electron electric dipole moment (eEDM) would violate time reversal symmetry. The Standard Model predicts an eEDM less than 10^{-38} e.cm, however many popular extensions predict values in the range 10^{-29} – 10^{-24} e.cm. Our experiment currently has the potential to measure eEDMs down to approximately 10^{-29} e.cm, making it a precise probe for T-violation and physics beyond the Standard Model.

We measure the eEDM by performing a type of separated oscillating field interferometry on a pulsed beam of YbF. The molecules are prepared such that the molecular spin is oriented perpendicular to an applied strong (10kV cm) electric field. The spin is then allowed to precess about the electric field axis over a 0.5ms interaction period. We measure this angle of rotation, which is directly proportional to the eEDM.

We report our current technique in more detail and present our most recent world leading result [1].

Reference

[1] Hudson, J. J., Kara, D. M., Smallman, I. J., Sauer, B. E., Tarbutt, M. R. and Hinds, E. A., *Improved measurement of the shape of the electron*, Nature **473**, 7348, pp. 493-U232 (2011).

Development of Fr ion source with melting Au target for electron EDM search

Tomohiro Hayamizu[1,*], Hidetomo P. Yoshida[2], Shan Liu[3], Saki Ezure[1], Kenichi Harada[1], Takeshi Inoue[1], Masatoshi Itoh[1], Tomohiro Kato[1], Hirokazu Kawamura[1], Huliyar S. Nataraj[1], Tomoya Sato[1], Takatoshi Aoki[4], and Yasuhiro Sakemi[1]

1. Cyclotron and Radioisotope Center (CYRIC), Tohoku University, Sendai, Miyagi, Japan
2. Research Center for Nuclear Physics (RCNP), Osaka University, Suita, Osaka, Japan
3. Jilin University, Changchun, Jilin, China
4. Graduate school of Arts and Science, University of Tokyo, Meguro, Tokyo, Japan
**hayamizu@cyric.tohoku.ac.jp*

A permanent electric dipole moment (EDM) in an elementary particle indicates the violation of the time-reversal (T) symmetry, whose evolution mechanism is important to understand the baryon asymmetry in the universe. In paramagnetic atoms, an electron EDM results in an atomic EDM enhanced by the atomic number Z. Francium (Fr, Z=87), which is the radioactive element, has the largest Z in alkali atoms and has the large enhancement factor of around 900. Laser cooling and trapping technique suppresses the systematic errors caused by the effects of $v \times E$ and inhomogeneous external fields. The high intensity Fr source is requested for the high sensitivity EDM search. Therefore, we have newly developed the high efficiency thermal ionizer for Fr ion production. We produce ^{210}Fr ($t_{1/2}$ = 3.2 min) with a nuclear fusion reaction $^{18}\mathrm{O} + ^{197}\mathrm{Au} \rightarrow ^{210}\mathrm{Fr} + 5\mathrm{n}$ using 100 MeV ^{18}O beam accelerated by the AVF cyclotron. Produced Fr is released as a Fr ion from heated Au target due to the effects of diffusion and surface ionization, and extracted in 5 kV electric field to transport to an ion to atom converter. We have observed the drastically increase of the Fr extraction yield and the efficiency from the ionizer when the Au target is melted.

Trial of cold antihydrogen beam extraction from a cusp trap for spectroscopic study of the ground-state hyperfine splitting of antihydrogen atom

N. Kuroda[1,*], H. Higaki[2], M. Ohtsuka[1], Y. Kanai[3], Y. Nagata[3], H. A. Torii[1], S. Ulmer[3], K. Michishio[4], K. Fujii[1], D. Murtagh[3], S. Sakurai[2], S. Takaki[1], B. Juhász[5], S. Federmann[5], M. Corradini[6], M. Leali[6], E. Lodi Rizzini[6], V. Mascagna[6], L. Venturelli[6], N. Zurlo[6], Y. Enomoto[3], Y. Matsuda[1], A. Mohri[3], Y. Nagashima[4], E. Widmann[7], and Y. Yamazaki[1,3]

1. University of Tokyo, Komaba, Tokyo, Japan
2. Hiroshima University, Higashi-Hiroshima, Japan
3. RIKEN, Wako, Japan
4. Tokyo University of Science, Kagurazaka, Tokyo, Japana
5. Stefan Meyer Institut für Subatomare Physik, Österreichische Akademie der Wissenschaften, Wien, Austria
6. Università di Brescia e INFN, Bresica, Italy
**kuroda@phys.c.u-tokyo.ac.jp*

The ASACUSA collaboration was succeeded in synthesizing cold antihydrogen atoms employing a cusp trap [1]. Althoug the cusp trap is not optimized to confine antihydrogen atoms, its magnetic field configuration preferentially focuses the low-field-seeking states of antihydrogen atom, which will results in the formation of a spin-polarized antihydrogen beam. By analogy of classical Rabi method, the ground-state hyperfine splitting of antihydrogen atom can be analyzed by such extracted antihydrogen beam together with a microwave cavity and a sextupole magnet in order to make a stringent test of the *CPT* symmetry. We recently obtained candidate signals from extracted cold antihydrogen beam, which has been making a path to realize the above measurement.

Reference

[1] Y. Enomoto *et al.*, Phy. Rev. Lett. **105**, 243401 (2010).

Resonant quantum transitions in trapped antihydrogen atoms

Andrea Gutierrez*, and the ALPHA collaboration

Department of Physics and Astronomy, University of British Columbia, Vancouver BC, V6T 1Z1, Canada
**andrea.gutierrez@triumf.ca*

Cold antihydrogen has been produced and, since 2010, trapped by the ALPHA (Antihydrogen Laser Physics Apparatus) experiment [1]. The antiatoms have been confined in the ALPHA magnetic trap for at least 1000 seconds [2], enabling further studies, including microwave and laser spectroscopy. Recently, microwave experiments have been carried out with antihydrogen inducing magnetic resonance transitions between hyperfine levels of the positronic ground state [3]. Such transitions lead the antiatom to be ejected from the magnetic trap. After applying radiation, the number of the antiatoms remaining in the trap were counted. When the radiation was on resonance, 0.02 antiatoms per experimental cycle were detected, compared to 0.21 when off resonance.

References
[1] Andresen, G. B. *et al.* "Trapped antihydrogen". Nature **468**, 673–676 (2010).
[2] Andresen, G. B. *et al.* "Confinement of antihydrogen for 1,000 seconds". Nature Phys. **7**, 558–564 (2011).
[3] Amole, C. *et al.* "Resonant quantum transitions in trapped antihydrogen atoms". Nature **483**, 439- 444 (2012).

Measurement of muonium hyperfine splitting at J-PARC

K. S. Tanaka[1,*], Y. Fukao[3], O. Kamigaito[2], N. Kawamura[3], Y. Matsuda[1], T. Mibe[3], T. Ogitsu[3], N. Saito[3], K. Sasaki[3], K. Shimomura[3], K. Suda[2], M. Sugano[3], M. Tajima[1], D. Tomono[2], H. A. Torii[1], A. Toyoda[3], and M. Yoshida[3]

1. Graduate School of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan
2. RIKEN Nishina Center for Accelerator Based Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
3. KEK, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
**tanaka@kaduo.jp*

We are planning a measuremnt of the ground state hyperfine structure of muonium at J-PARC/MLF. Muonium is a hydrogen-like bound state of leptons, and its HFS is a good probe for testing QED theory. The muon mass m_μ and magnetic moment μ_μ which are fundamental constants of muon have been so-far determined by the muonium HFS experiment at LAMPF [1]. The high intensity beam soon to be available at J-PARC allows one order of magnitude more accurate determination of those constants, which also plays an important role in the new measurement of anomalous magnet monment.

Reference
[1] W. Liu *et al.*, High precision measurements of the ground state hyperfine structure interval of muonium and of the muon magnetic moment, Phys. Rev. Lett., **82**, pp. 711-714 (1999).

The new francium trapping facility at TRIUMF

S. Aubin[1], J. A. Behr[2], R. A. Collister[3], E. Gomez[4], G. Gwinner[3], V. V. Flambaum[5], D. G. Melconian[6], L. A. Orozco[7,*], M. R. Pearson[2], G. D. Sprouse[8], M. Tandecki[2,3], J. Zhang[7], and Y. Zhao[9]

1. College of William and Mary,Williamsburg VA, USA
2. TRIUMF, Vancouver, BC, Canada
3. University of Manitoba, Winnipeg, Manitoba, Canada
4. Universidad Autónoma de San Luis Potosí, San Luis Potosí, SLP, México
5. University of New South Wales, Sydney, NSW, Australia
6. Texas A&M, College Station, TX, USA
7. University of Maryland, College Park, MD, USA
8. University at Stony Brook, Stony Brook, NY, USA
9. Shanxi University, Taijuan, Shanxi, China
**lorozco@umd.edu*

We are constructing the francium trapping facility at TRIUMF and we planning on a commissioning run in 9-2012. Fr is an ideal atom for atomic spectroscopy studies of the weak interaction due to its high nuclear charge and relatively simple electronic structure. We are preparing experiments to study the hyperfine anomaly, the anapole moment, and optical parity non-conservation (PNC) in chains of isotopes. The hyperfine anomaly gives information on the spatial distribution of the nuclear magnetization. The anapole moment dominates the nuclear spin dependent part of the PNC electron-nucleus interaction and allows the study of the weak interaction inside the nucleus. The optical PNC measurement of nuclear spin independent PNC is sensitive to physics beyond the standard model.
Work supported by NSERC and NRC from Canada, NSF and DOE from USA.

The orbital magnetism of relativistic atomic electrons

M. Awobode

Department of Physics, University of Ibadan, Ibadan, Nigeria
awobode@gmail.com

We consider a possible correction to the orbital magnetic moment of bound electrons. In condensed matter systems, the correction manifests as new phenomena at low temperatures and high magnetic fields. Here we investigate the possibility of detecting, by means of enhanced Atomic Beam Resonance Zeeman technique, the corrections to the orbital magnetic moment of the atomic electrons. It is suggested that the correction may be best observed in alkali metal atoms.

References

[1]. A. M. Awobode, Il Nuovo Cimento, Vol. 121B, no 6 (2006), p. 563.
[2]. A. M. Awobode, Bull. Am. Phys. Soc., Vol. 54, no 4, (2009), p. 243.
[3]. A. M. Awobode, Bull. Am. Phys. Soc., Vol. 57, no 3 (2012), p. 157.

Quantum statistics in a Gaussian Potential

M. D. Hoogerland* and S. S. Shamailov

University of Auckland, Department of Physics, Private Bag 92019, Auckland, New Zealand
**m.hoogerland@auckland.ac.nz*

We investigate Gaussian potentials by solving the time-independent Schrödinger equation directly, and obtain a number of empiric relationships between the number of states, their energies and the potential depth, potential width and particle mass.

We compare our findings with recent results on the spectroscopy of fermionic ^{3}He in a dipole trap, formed by a pair of crossed laser beams [1]. They found that the number of trapped atoms was remarkably constant over multiple instances of the same experiment at low laser power. We interpret this as caused by every available state of the trap being filled by one atom. ing them in a bath of bosons, the atoms would occupy the lowest states available. At the conference, we will compare our results with the experimental data, and discuss analytical approximations to the density of states.

Reference

[1] R. van Rooij, J. S. Borbely, J. Simonet, M. D. Hoogerland, K. S. E. Eikema, R. A. Rozendaal and W. Vassen, Science **333**, 196–198, 2011.

Electric dipole moment enhancement factor of thallium

S. G. Porsev[1,2], M. S. Safronova[1,*], and M. G. Kozlov[2]

1. Department of Physics and Astronomy, University of Delaware, Newark, DE, USA
2. Petersburg Nuclear Physics Institute, Gatchina, Russia
**msafrono@udel.edu*

A number of extensions of the standard model of particle physics predict electric dipole moments (EDM) of particles that may be observable with the present state-of-the art experiments making EDM studies a remarkable tool in search for new physics. The electron EDM is enhanced in certain atomic and molecular systems, and two of the most stringent limits on the electron EDM d_e were obtained from the experiments with ^{205}Tl [Regan *et al.*, PRL 88, 071805 (2002)], and with YbF molecule [Hudson *et al.*, Nature 473, 493 (2011)]. Both results crucially depend on the calculated values of the effective electric field on the valence electron. In the case of Tl this effective field is proportional to the applied field E_0, $E_{\rm eff} = KE_0$, and $d(^{205}\mathrm{Tl}) = Kd_e$. The goal of this work is to resolve the present controversy in the value of the EDM enhancement factor K in Tl. We have carried our several calculations by different methods, and find the EDM enhancement factor of Tl to be equal to – 573(20). This value is 20% larger than the recently published result of Nataraj *et al.* [Phys. Rev. Lett. **106**, 200403 (2011)], but agrees very well with several earlier results.

High resolution spectroscopic study of the $A^1\Sigma^+$-$b^3\Pi$ complex in RbCs molecule

Artis Kruzins[1,*], Kalvis Alps[1], Olga Docenko[1], Ilze Klincare[1], Maris Tamanis[1], Ruvin Ferber[1], Andrey V. Stolyarov[2], and Elena A. Pazyuk[2]

1. Department of Physics, University of Latvia, Riga, Latvia
2. Department of Chemistry, Moscow State University, Moscow, Russia
**artis.kruzins@fizmati.lv*

In alkali diatomic molecules containing heavy heteronuclear atoms the lowest excited $A^1\Sigma^+$ and $b^3\Pi$ states, due to the strong spin-orbit interaction, are strongly coupled. These fully mixed states can't be separated and thus need to be considered as a single $A^1\Sigma^+$-$b^3\Pi$ (A-b) complex with complicated energy levels structure as shown in [1].The goal of the present study was to extend data field and to improve accuracy of the complex description applying 4-chaneldeperturbation model. In the experiment A-b complex is studied using either direct excitation by diode lasers, or excitation of the $(4)^1\Sigma^+$ state with observation of laser induced fluorescence (LIF) $(4)^1\Sigma^+ \rightarrow$ A-b. LIF spectra were recorded by Fourier transform spectrometer Bruker IFS 125HR with the resolution of 0.03 – 0.05 cm^{-1}. More than 4600 A-b complex term values for $^{85}Rb^{133}Cs$ were obtained in energy range $E \in [10066,12857]$ cm^{-1}). Elaborated deperturbation model reproduces data with experimental accuracy (better than 0.01 cm^{-1}).

Reference
[1] O. Docenko, M. Tamanis, R. Ferber, T. Bergeman, S. Kotochigova, A. V. Stolyarov, Andreia de Faria Nogueira, and C. E. Fellows , *Spectroscopic data, spin-orbit functions, and revised analysis of strong perturbative interactions for the $A^1\Sigma^+$ and $b^3\Pi$ states of RbCs*, Physical Review A **81**, 042511 (2010).

Multipass cell with confocal mirrors for sensitive broadband laser spectroscopy in the near IR

T. Mohamed[1,2], F. Zhu[1], J. Strohaber[1], A. Kolomenskii[1], and H. A. Schuessler[1,2,*]

1. Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
2. Science Department, Texas A&M University at Qatar, Doha 23874, Qatar
**schuessler@physics.tamu.edu*

An optical multi-pass cell based on highly reflecting confocal mirrors to achieve both long optical paths and dense atom space (volume) coverage has been developed. Using six mirrors, we demonstrate a path-length of 300 m in a cell of only of 0.5 m in length. Different volume filling and path lengths were achieved by tilting the mirrors with angles ≤ 0.05 radians. Spectrally resolved absorption measurements in the near IR of the greenhouse gases CO_2, CO, and CH_4 were carried out with a broadband frequency comb Er+ fiber laser beam, extended by Raman shifting in a highly nonlinear fiber to a range of 1.45 to 1.75 microns. The absorption spectra were recorded using a spectrum analyzer and showed rovibrational resolution and a sensitivity of a few ten ppmv. The optical apparatus is portable and can be used for a wide range of applications, including environmental monitoring, combustion processes, medical diagnostics, and fundamental atomic and molecular physics studies. This research is supported by the Qatar Foundation under the NPRP grant 09 - 585 - 1 – 087.

Confining a vapour in a nanostructure yields a sub-Doppler resolution in linear spectroscopy

Philippe Ballin, Elias Moufarej, Isabelle Maurin, Athanasios Laliotis, and Daniel Bloch*

Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris-Cité
and
CNRS, UMR 7538, 99 Avenue J-.B. Clément, F-93430 Villetaneuse, France
**daniel.bloch@univ-paris13.fr*

We show that a dilute alkali thermal vapour can be confined in the sub-micrometric interstitial regions of an opal of glass nanospheres, in a regime where the production of clusters is negligible. With a vapour cell whose window is covered with a film made of 10 or 20 layers of glass spheres (diameter ~1μm, or even 400nm), we perform linear reflection spectroscopy across the Cs resonance lines. We thus observe sub-Doppler structures on the optical spectrum, for a large range of acceptance angles, including very oblique incidence (~ 30-50°). These narrow contributions to the optical spectrum are proved to originate in the 3-D vapor confinement, and are reminiscent of the Dicke narrowing [1], well-known in the r.f. domain in the presence of a collision confinement effect, but elusive in the optical frequency range. These narrow structures allow envisioning compact optical frequency references; moreover, the linearity of the technique offers applicability to weak molecular lines.

Reference

[1] R. H. Dicke, The effect of collisions upon the Doppler width of spectral lines, Phys. Rev. **89**, 472 (1955).

Toward to a new definition of the kelvin: accurate determination of the Boltzmann constant via spectral-line Doppler broadening

S. Mejri, P. L. T. Sow, C. Lemarchand, B. Darquié, Ch. J. Bordé, C. Chardonnet, and C. Daussy

Laboratoire de Physique des Lasers, CNRS/Université Paris 13, 99 av. J-B. Clément, 93430 Villetaneuse, France
**sinda.mejri@univ-paris13.fr*

In the current International System of Units (SI), the definition of the kelvin is linked to a material property, namely the triple point temperature of the water. Aiming to dissociate this definition to any artifact, efforts are made towards a new definition of the kelvin via an unchangeable fundamental constant: the Boltzmann constant, k_B. For this purpose k_B must be determined with an uncertainty at the ppm level. Precision laser spectroscopy applied to an isolated line of ammonia in the 10 μm region, combined with highly accurate measurement of the absorption line shape and the use of refined methods of lineshape fitting and analysis, has recently allowed measurements of k_B by laser spectroscopy [1]. Spectra recorded are analyzed with various models that take into account Dicke narrowing or speed-dependant effects of collisional parameters.

The present work indicates that a first determination of k_B with a competitive uncertainty of a few ppm is reachable [2]. It will then be worthily compared the value obtained by the acoustic method and thus hopefully contribute significantlyto the new value of k_B determined by the Committee on Data for Science and Technology (CODATA).

References

[1] C. Lemarchand *et al.*, New J.Phys **5**, 13, 073028 (2011).
[2] M. Triki *et al.*, arXiv:1201.4087v1 **5**, (2012).

Narrow linewidth, hybrid integrated extended cavity diode lasers for precision quantum optics experiments in space

Erdenetsetseg Luvsandamdin[1,*], Christian Kürbis[1], Stefan Spiessberger[1], Alexsander Sahm[1], Andreas Wicht[1, 2], Goetz Erbert[1], Günther Tränkle[1], and Achim Peters[2]

1. Ferdinand-Braun Institut, Leibniz Institut für Hoechstfrequenztechnik, Berlin, Germany
2. Humboldt University zu Berlin, Germany
**luvsandamdin@fbh-berlin.de*

We present a very compact, robust, and narrow linewidth extended cavity diode laser (ECDL) for precision quantum optics applications in space or in a micro-gravity environment. It will be used for Rubidium BEC and atom interferometry experiments on board a sounding rocket to be launched in 2013. The micro-integrated ECDL is based on a Littrow configuration and omits all moveable parts to guarantee excellent mechanical stability. Laser chip, micro-optics, and electronical components are integrated on a structured aluminum nitride ceramic body that only weights 40 grams and takes up a voulme of 30 cm^3. The ECDL provides a continuous tuneability of more than 30 GHz by synchronizing the temperature of the VHBG and the injection current. In heterodyne beat note measurements we have demonstrated an intrinsic linewidth of 300 Hz full-width-at-half-maximum (FWHM) and 60 kHz FWHM short term (170 μs) linewidth (including technical noise) at an output power of 35 mW. We further report on results of mechanical vibration tests that simulate the mechanical load of a sounding rocket launch.

Odd-photon cancellation effect and the cooperative Lamb shift

Natalia R. de Melo* and Sandra S. Vianna

Departamento de Física, Universidade Federal de Pernambuco, 50670-901 Recife, PE, Brazil
**natalia.rmelo@gmail.com*

Recently, the cooperative Lamb shift (CLS) phenomenon was shown to play a prominent role for the explanation of the frequency shift observed in single-photon superradiance [1] and in an atomic vapor layer with tunable thickness and atomic density [2]. Here, we report on a four-wave mixing process in Rb vapor where three-photon atomic excitation is produced by two laser beams, which are crossed at an angle θ. At high density and for small θ, a suppression of the generated signal occurs near the unperturbed three-photon resonance; notwithstanding, a large shift is observed in the peak position, which decreases as the θ angle increases. The suppression effect is due to a destructive interference between different pathways induced by the incident beams and by the four-wave-mixing field. The shift dependence on θ and on the atomic density are in agreement with the description based on CLS, where the shifted resonance is near the frequency required for phase matching [3].

References

[1] R. Röhlsberger, K. Schlage, B. Sahoo, S. Couet, R. Rüffer, *Collective Lamb Shift in Single-Photon Superradiance*, Science **328**, pp. 1248-1251 (2010).
[2] J. Keaveney, A. Sargsyan, U. Krohn, I. G. Hughes, D. Sarkisyan, C. S. Adams, *Cooperative Lamb Shift in an Atomic Vapor Layer of Nanometer Thickness*, Phys. Rev. Lett. **108**, pp. 173601 (2012).
[3] W. R. Garrett, R. C. Hart, J. E. Wray, I. Datskou, M. G. Payne, *Large Multiple Collective Line Shifts Observed in Three-Photon Excitations of Xe*, Phys. Rev. Lett. **64**, pp. 1717-1720 (1990).

Noise correlation spectroscopy in EIT with cold atoms

Hans Marin[1,*], Luciano Cruz[2], Daniel Felinto[3], Jose W. Tabosa[3], Marcio M. Miranda[1]
P. Nussenzveig[1], and Marcelo Martinelli[1]

1. Instituto de Física, Universidade de São Paulo, 05315-970 São Paulo, SP-Brazil
2. Universidade Federal do ABC, Santo André, SP-Brazil
3. Departamento de Física, Universidade Federal de Pernambuco, 50670-901 Recife, PE-Brazil
**hansmf@usp.br*

Using noise espectroscopy, we studied the correlation between two laser beams with opposite circular polarizations, coupling the transition ${}^5S_{1/2}F=2$ to ${}^5P_{3/2}F'=2$ in Electromagnetically Induced Transparency (EIT), using cold atoms of ^{85}Rb. We observed the transition from correlation to anti-correlation, between the probe and control beams, when their intensity was increased [1,2]. The cross-correlation spectra, contrary to the mean value of the intensities, shows a EIT peak, that is free of power broadening [4], which experimentally allows the direct measurement of coherence time between the ground states in EIT condition. The Phase Difusion model [3] applied to EIT systems with three levels in Λ configuration [2], predicts this non-broadening of the correlation peak, showing the correlation as a more accurated characterization property than the mean value of intensity.

References

[1] Vladimir A. Sautenkov *et al.* Phys. Rev. A., **72** (065801), 2005.
[2] L. S. Cruz *et al.*, Eur. Phys. J. D., **41**, 531-539, (2006).
[3] T. Yabuzaki *et al.*, Phys. Rev. Lett., **67**, 2453 (1991).
[4] Yanhong Xiao *et al.*, Phys. Rev. A. **80**, 041805(R) (2009).

Doubly excited states of helium-like Cl

J. P. Santos[1,*], A. M. Costa[1], P. Indelicato[2], S. Kasthurirangan[3], J. K. Saha[4],
A. Banerjee[5], A. Agnihotri[5], S. Bhattacharyya[6], D. Misra[5], A. Kumar[7],
P. K. Mukherjee[8], L. C. Tribedi[5], and T. K. Mukherjee[4]

1. Centro de Física Atómica, FCT, Universidade Nova de Lisboa, P-2829-516 Caparica, Portugal
2. LKB, ENS, CNRS, UPMC, Case 74, 4, place Jussieu, 75252 Paris Cedex 05, France
3. Institute of Chemical Technology, Matunga, Mumbai 400019, India
4. Narula Institute of Technology, Agarpara, Kolkata-700109, India
5. Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400 005, India
6. Acharyya Prafulla Chandra College, New Barrackpore, Kolkata-700131, India
7. NPD, Bhabha Atomic Research Centre, Mumbai 400 085, India
8. Ramakrishna Mission Vivekananda University, Belur, Howrah, West Bengal 711202, India
**jps@fct.unl.pt*

In the last decade, it has been found that some discrete doubly excited states (DES) embedded in continuum, like the 2p3d ($^1P^o$) state, in spite of being autoionizing are fluorescence active. In this work, we have performed both non-relativistic and relativistic calculations for the transitions of several DES of helium-like Cl. Our present calculation shows that the fluorescence probability of the 2p3d ($^1P^o$) state of Cl^{15+} is still almost 10 times larger than its autoionization probability. The dominance of fluorescence decay over autoionization of the 2p3d ($^1P^o$) state of highly charged ions are being verified experimentally for the first time. The calculated energy value for the 2p3d ($^1P^o$) → 1s3d ($^1D^e$) transition is in excellent agreement with those of the observed values of Cl^{15+}.

Supersolid and quantum magnetic phases with mixtures of Bose-condensed rubidium and degenerate fermionic lithium

Subhadeep De, Daniel L. Campbell, Ryan M. Price, Andika Putra, and Ian B. Spielman

Joint Quantum Institute, Maryland
University of Maryland, College Park and National Institute of Standard and Technology, Gaithersburg, USA
**sde.subhadeep@gmail.com*

We propose to use a spin-polarized, non-interacting, degenerate ^{6}Li gas mixed with ^{87}Rb atoms to generate coupling between distant bosons due to successive interspecies scattering. The interaction has R^{-4} spatial dependence. Unlike the dipole-dipole interaction, the strength of the fermion mediated Bose-Bose interaction can be either attractive or repulsive with the help of interspecies Feshbach resonances. The loss process due to three-body recombination will greatly be suppressed in the Mott phase of bosons. A mixture of heavy bosons and light fermions is ideal because a lattice will localize bosons while fermions can move freely. We further investigate schemes to create supersolid and quantum magnetic phases in bosons with the help of the fermion mediated interactions. We are engaged in building an apparatus to produce the mixtures of degenerate ^{87}Rb and ^{6}Li gases. Currently the machine is commissioning the ^{87}Rb BEC and DFG of ^{6}Li is in the pipeline. We are studying topological defect formation by Kibble-Zurek mechanism in ^{87}Rb spinor BEC at the $F = 1$ hyperfine state.

Bose gases Th-046

Phase space theory of BEC and time dependent modes

Bryan Dalton

Centre for Atom Optics and Ultrafast Spectroscopy and Centre for Quantum-Atom Optics, Swinburne University of Technology, Melbourne, Victoria 3193, Australia
bdalton@swin.edu.au

Phase space theories where highly occupied condensate modes and mainly unoccupied non-condensate modes are respectively treated via a hybrid double space Wigner and positive P distribution functional, have been developed [1,2], and may be applied to various BEC evolution problems, such as BEC interferometry experiments with interacting bosonic atoms in time varying double well traps at very low temperatures [1]. The present paper extends work in [1] showing that extra terms are present in the functional Fokker-Planck and Ito stochastic field equations due to using time dependent mode functions. These are obtained via coupled Gross-Pitaevskii mean field equations which can provide a good first approximation for condensate bosons. The extra terms involve coupling coefficients defined by integrals of the mode functions with their time derivatives.

References

[1] B. J. Dalton, "Theory of Decoherence in BEC Interferometry", J. Phys. Conf. Ser. **67**, 012059: 1-5 (2007); "Decoherence Effects in BEC Interferometry, I General Theory", Ann. Phys. **326**, pp. 668-720 (2011).
[2] S. E. Hoffmann, J. F. Corney and P. D. Drummond, "Hybrid Phase-Space Simulation Method for Interacting Bose Fields", Phys. Rev. A **78**, 013622: 1-12 (2008).

Relaxation dynamics and pre-thermalization in an isolated quantum system

Tim Langen[1,*], Michael Gring[1], Maximilian Kuhnert[1], Bernhard Rauer[1], Igor Mazets[1], David A. Smithript[1], Remi Geiger[1], Takuya Kitagawa[2], Eugene Demler[2], and Jörg Schmiedmayer[1]

1. Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Wien, Austria
2. Harvard-MIT Center for Ultracold Atoms, Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
**tlangen@ati.ac.at*

Understanding relaxation processes is an important unsolved problem in many areas of physics. A key challenge in studying such non-equilibrium dynamics is the scarcity of experimental tools for characterizing their complex transient states. We employ measurements of full quantum mechanical probability distributions of matter-wave interference to study the relaxation dynamics of a coherently split one-dimensional Bose gas and obtain unprecedented information about the dynamical states of the system. Following an initial rapid evolution, the full distributions reveal the approach towards a thermal-like steady state characterized by an effective temperature that is independent from the initial equilibrium temperature of the system before the splitting process. We conjecture that this state can be described through a generalized Gibbs ensemble and associate it with pre-thermalization.

Effects of tunable exchange symmetry for interacting bosons

Malte C. Tichy*, Jacob F. Sherson, and Klaus Mølmer

Lundbeck Foundation Theoretical Center for Quantum System Research, Department of Physics and Astronomy, University of Aarhus, DK–8000 Aarhus C, Denmark
**tichy@phys.au.dk*

Quantum many-body dynamics, such as they are observed in experiments with ultracold atoms, rely on the inter-particle interaction as well as on exchange effects induced by the bosonic or fermionic nature of the particles. The interplay of these phenomena is studied here by means of a mixture of several species that do not differ in their physical properties. The total population imbalance of such a bosonic mixture in the double-well can be described effectively by a single species, in a potential with modified properties or, equivalently, with an effective total particle number. The self-trapping or oscillating behavior of the mixture can thus be tuned to a wide extent by the population balance of the two species. The approach is extended to general Bose-Hubbard systems and to their classical mean-field limits, which suggests an effective description of the particle density of Bose gases of several components that weakly differ in their physical properties.

Steady state structures of two-species Bose-Einstein condensates

Robert W. Pattinson[1,*], Thomas P. Billam[2], Simon A. Gardiner[2], Daniel J. McCarron[2], Hung-Wen Cho[2], Simon L. Cornish[2], Nick G. Parker[1], and Nick P. Proukakis[1]

1. Joint Quantum Centre(JQC) Durham–Newcastle, School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
2. Joint Quantum Centre(JQC) Durham–Newcastle, Department of Physics, Durham University, Durham, DH1 3LE, UK
**r.w.pattinson@ncl.ac.uk*

In a recent experiment [1] a two-species condensate was formed via sympathetic cooling and three distinct regimes of density distributions observed depending on atom numbers. To reproduce these theoretically, we investigate time-independent solutions through zero-temperature mean-field simulations. We find the results to be sensitive to experimentally relevant shifts in the potentials in both longitudinal and transverse directions and observe a range of structures, including 'ball and shell' formations or axially/radially separated states. We find good overall agreement for all regimes. Due to rapid sympathetic cooling, condensate growth likely plays an important role, an effect we study by incorporating this into our mean–field description.

Reference
[1] D. J. McCarron *et al.*, *Dual-species Bose-Einstein condensate of* ^{87}Rb *and* ^{133}Cs, PRA **84**, 011603 (2011).

Numerical studies of non-equilibrium dynamics during the condensation of binary bosonic mixtures of ^{87}Rb and ^{133}Cs using stochastic projected Gross-Pitaevskii equation

I.-K. Liu[1], H.-W. Cho[3], S.-W. Su[2], D. J. McCarron[3], S. L. Cornish[3], and S.-C. Gou[1]

1. Department of Physics, National Changhua University of Education, Changhua 50085, Taiwan
2. Deparment of Physiscs, National Tsing Hua University, Hsinchu 30047, Taiwan
3. Department of Physics, Durham University, Durham DH1 3LE, UK

The realization of dual-species Bose-Einstein condensate (BEC) of ^{87}Rb and ^{133}Cs using sympathetic cooling were reported by McCarron *et al.* [1]. It was found that the density profiles exhibit phase-separated structures, including the ball(Cs)-shell(Rb), ball(Rb)-shell(Cs) and asymmetric phases, due to the immiscible interaction condition [1,2]. In this presentation, we employ the stochastic projected Gross-Pitaevskii equation (SPGPE) to simulate the growth of dual-species condensate [3] during the cooling. The numerical results based on the SPGPE method are consistent with the experiments [1]. We find that the ball-shell phases are long-lived metastable states which will, eventually, either evolve to the asymmetric phase, or one of the two species become stillborn.

References
[1] D. J. McCarron *et al.*, Phys. Rev. A **84**, 011603(R) (2011).
[2] A. D. Lercher *et al.*, Eur. Phys. J. D (2011), doi:10.1140/epjd/ e2011-20015-6.
[3] P. Blair Blakie and Matthew J. Davis, Phys. Rev. A **72**, 063608 (2005).

Vortex-sound interactions in trapped Bose-Einstein condensates

Nick G. Parker, Joy Allen, Carlo F. Barenghi, and Nick P. Proukakis

Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics,
Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
**nick.parker@newcastle.ac.uk*

Within a superfluid, circulating flow is constrained to occur via quantized vortices. At zero temperature, where sound modes provide the ultimate energy sink in the system, quantized vortices undergo decay via emission of sound waves during their acceleration or a reconnection event.

In a trapped Bose-Einstein condensate, this is only half the story. Here, the finite system size forces the emitted sound to re-interact with the vortex. We demonstrate that the non-trivial vortex-sound interactions, including emission and absorption processes, can be elucidated in a double-well trap: with one vortex in each well, the sound emitted by each precessing vortex can be driven into the opposing vortex. This "cross-talk" leads to a periodic exchange of energy between the vortices which is long-range and highly efficient. The increase in vortex energy is significant and should be experimentally observable at low temperatures as a migration of the vortex to higher density over a few precession periods. Similar effects can be controllably engineered by introducing a precessing obstacle into one well as an artificial generator of sound, thereby demonstrating the parametric driving of energy into a vortex.

Reference

[1] N. G. Parker, A. J. Allen, C. F. Barenghi and N. P. Proukakis, *Coherent cross-talk and parametric driving of matter-wave vortices*, arXiv:1109.0039 (2011).

Finite temperature vortex dynamics in trapped Bose gases

Joy Allen[1,*], Carlo F. Barenghi[1], Eugene Zaremba[2], and Nick P. Proukakis[1]

1. Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics,
Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
2. Department of Physics, Queens University, Kingston, Ontario, K7L 3N6, Canada
**joy.allen@ncl.ac.uk*

We study the precession of an off-centered vortex in a finite temperature, harmonically-trapped atomic condensate. In the absence of a thermal cloud, it is well understood the vortex rotates at a constant radius, as recently confirmed experimentally [1]. However, the thermal cloud induces a frictional force on the vortex, thereby leading it to a gradual decay. By an extension of earlier work [2], we perform a detailed quantitative study of the role of the dynamics of the thermal cloud on the experimentally-relevant quantities of vortex decay rate and precession frequency, highlighting the importance of the various collisional processes involved. We model the system by a dissipative Gross-Pitaevskii equation for the condensate, self-consistently coupled to a quantum Boltzmann equation for the thermal modes, which additionally includes collisional processes which transfer atoms between these two subsystems (Zaremba-Nikuni-Griffin formalism, 'ZNG') [3].

References

[1] D. V. Freilich, D. M. Bianchi, A. M. Kaufman, T. K. Langin, D. S. Hall, Science **329**, 1182 (2010).
[2] B. Jackson, N. P. Proukakis, C. F. Barenghi, and E. Zaremba, PRA **79**, 053615 (2009).
[3] E. Zaremba, T. Nikuni, and A. Griffin, JLTP **116**, 277 (1999).

Temperature dependence of three-body losses in unitary Bose gases

Benno Rem[1,*], Igor Ferrier-Barbut[1], Ulrich Eismann[1], Andrew Grier[1], Tim Langen[2], Andrea Bergschneider[1], Frédéric Chevy[1], and Christophe Salomon[1]

1. Laboratoire Kastler Brossel, ENS, UPMC, CNRS UMR 8552, Paris, France
2. Vienna Center for Quantum Science and Technology, Vienna, Austria
**benno.rem@lkb.ens.fr*

Recently, new thermodynamic methods applied to cold atoms have permitted the precise measurement of the equation of state of strongly interacting Fermi gases. In contrast to fermions, experiments on strongly interacting Bose gases are limited due to three-body losses. In the low temperature regime, interactions between ultra-cold atoms are described by a single parameter: the s-wave scattering length a. In 1996, an a^4 dependence on the atomic three-body recombination loss rate L_3 was predicted [1]. However, due to finite temperature effects, a limit on the recombination rate is imposed at unitarity, where $(k\,|\,a\,|)^{-1} \to 0$, such that L_3 does not diverge [2]. We will introduce existing theoretical predictions of temperature-dependence of the unitarity-limited, three-body loss rate. Furthermore, we will present measurements of the variation of the three-body loss rate with temperature, that clarifies the temperature range over which the unitary Bose gas is metastable and can be studied in the framework of thermodynamics [3].

References
[1] P. Fedichev, M. Reynolds, G. V. Shlyapnikov, *Physical Review Letters* **77** (1996) 2913.
[2] C. H. Greene, B. D. Esry, H. Suno, *Nuclear Physics A* **737** 119-124 (2004).
[3] W. Li, T.-L. Ho, arXiv:1201.1958.

Rotation of a spin-orbit-coupled Bose-Einstein condensate

Peter Mason[1,*] and Amandine Aftalion[2]

1. Department of Physics, Durham University, Durham DH1 3LE, UK
2. UVSQ, LMV, Versailles Cédex, France
**peter.mason@durham.ac.uk*

Recent experiments [1] have engineered spin-obit (SO) coupling in a neutral atomic Bose-Einstein condensate through the dressing of two atomic spin states with a pair of lasers. This has led to an interest in the application of these systems, such as for spintronic devices. The addition of rotation to the system adds non-trivial topological defect effects. We consider a mean-field description of the rotating spin-1/2 Bose-Einstein condensate with spin-orbit interactions. Through a Thomas-Fermi approximation and working in the non-linear sigma model formalism, we are able to determine regimes of different topological defects and ground state profiles. We back these analytical results up with a series of numerical simulations on the full Gross-Pitaevskii equation. In particular, these simulations provide a series of phase diagrams according to the crucial parameters present in the system: the spin-coupling, the rotation frequency and the interaction strengths.

Reference
[1] Y.-J. Lin, K. Jimenez-Garcia & I. B. Spielman, *Spin-orbit-coupled Bose-Einstein condensates*, Nature **471**, pp. 83-86 (2011).

Stationary states of trapped spin-orbit-coupled Bose-Einstein condensates

Emmi Ruokokoski[1], Jukka Huhtamäki[1], and Mikko Möttönen[1,2]

1. Department of Applied Physics/COMP, Aalto University, P.O. Box 14100, FI-00076 AALTO, Finland
2. Low Temperature Laboratory, Aalto University, P.O. Box 13500, FI-00076 AALTO, Finland
**emmi.ruokokoski@aalto.fi*

We investigate the stationary states of spin-1 Bose-Einstein condensates in the presence of Rashba–Dresselhaus-type spin-orbit coupling. Previously this coupling has been predicted to generate exotic ground-state structures. We numerically study the energies of various stationary states as functions of the spin-orbit coupling strength and determine the ground states of the condensates. Our results indicate that for strong spin-orbit coupling, the ground state is a square vortex lattice, irrespective of the value of the spin-spin coupling. For weak spin-orbit coupling, the lowest-energy state may host a single vortex. Furthermore, starting from the homogeneous approximation, we analytically derive constraints that explain why certain stationary states do not emerge as ground states. Importantly, we show that the distinct stationary states can be observed experimentally by standard time-of-flight spin-independent absorption imaging.

Reference

[1] E. Ruokokoski, J. A. M. Huhtamäki, M. Möttönen, *Stationary States of Trapped Spin-Orbit-Coupled Bose–Einstein Condensates*, arXiv:1205.4601 (2012).

Correlations and coherence in ultracold atomic gases

S. S. Hodgman[1,2], Wu RuGway[1], R. G. Dall[1], A. G. Manning[1], K. G. H. Baldwin[1,*], and A. G. Truscott[1]

1. ACQAO, RSPE, Australian National University, Canberra, ACT 0200 Australia
2. Max-Planck-Institut für Quantenoptik, Garching b. München, Germany
**Kenneth.Baldwin@anu.edu.au*

In experiments with Bose-Einstein condensates we have demonstrated that in direct analogy with lasers, BECs possess long range coherence to at least third order [1]. This analogy with light extends to incoherent sources where the presence of atom bunching in second order correlations (the Hanbury Brown – Twiss effect) is characteristic of matter wave speckle [2]. In these experiments we make use of the ability to detect single atoms of helium in the metastable 2^3S_1 state which allow direct determination of the quantum statistics [3]. Most recently, we have investigated higher order correlations in a one-dimensional Bose gas. In such a system the transverse dimension can condense before full 3-D condensation resulting in a multi-mode condensate. Such a gas exhibits almost perfect bunching and has enabled the measurement of correlation functions up to fifth order.

References

[1] S. S. Hodgman *et al.* "Direct measurement of long-range third-order coherence in Bose-Einstein condensates", *Science* **331**, 1046 (2011).
[2] R. G. Dall *et al.,* "Observation of atomic speckle and Hanbury Brown - Twiss correlations in guided matter waves", *Nature Communications* **2**:291 doi: 10.1038/ncomms1292 (2011).
[3] W. Vassen *et al.*, "Cold and trapped metastable noble gases", Rev. Mod. Phys. **84**, 175 (2012).

Laser driving of superradiant scattering from a Bose-Einstein condensate at variable incidence angle

Xiaoji Zhou*, X. G. Yue, Y. Y. Zhai, Z. K. Wang, T. Vogt, and Xuzong Chen

School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, People's Republic of China
**xjzhou@pku.edu.cn*

We study superradiant scattering from a Bose-Einstein condensate using a pump laser incident at variable angle and show the presence of asymmetrically populated scattering modes. Experimental data reveal that the direction of the pump laser plays a significant role in the formation of this asymmetry, a result which is in good agreement with numerical simulations based on coupled Maxwell-Schrodinger equations. Our study complements the gap of previous work in which the pump laser was applied only along the short axis or the long axis of a condensate, and extends our knowledge about cooperative scattering processes [1]. Based on this analysis, by a coherent Bragg diffraction method we measure the multiband energy structures of single-particle excitations , which reveal the interaction effect through the whole range of lattice depths [2].

References
[1] B. Lu, X. J. Zhou, T. Vogt, Z. Fang, and X. Z. Chen, Phys. Rev. A 83, 033620 (2011).
[2] X. Liu, X. J. Zhou, W. Zhang, T. Vogt, B. Lu, X. Yue, X. Z. Chen, Phys. Rev. A 83, 063604 (2011).

Bose gases Th-058

Superfluid behaviour of a two-dimensional Bose gas

Rémi Desbuquois*, Lauriane Chomaz, Tarik Yefsah, Julian Léonard,
Jérôme Beugnon, Christof Weitenberg, and Jean Dalibard

Laboratoire Kastler Brossel, CNRS, UPMC, Ecole Normale Supérieure, 24 rue Lhomond, F-75005 Paris, France
**remi.desbuquois@ens.fr*

Two-dimensional (2D) systems play a special role in many-body physics. Because of thermal fluctuations, they cannot undergo a conventional phase transition associated to the breaking of a continuous symmetry. Nevertheless they may exhibit a phase transition to a state with quasi-long range order via the Berezinskii-Kosterlitz-Thouless (BKT) mechanism. A paradigm example is the 2D Bose fluid, such as a liquid helium film, which cannot Bose-condense at non-zero temperature although it becomes superfluid above a critical phase space density. Ultracold atomic gases constitute versatile systems in which the 2D quasi-long range coherence and the microscopic nature of the BKT transition were recently explored. However, a direct observation of superfluidity in terms of frictionless flow is still missing for these systems. Here we probe the superfluidity of a 2D trapped Bose gas with a moving obstacle formed by a micron-sized laser beam. We find a dramatic variation of the response of the fluid, depending on itsdegree of degeneracy at the obstacle location. In particular we do not observe any significant heating in the central, highly degenerate region if the velocity of the obstacle is below a critical value.

Collision of oblique dark solitons in the two-dimensional supersonic nonlinear flow

Eder S. Annibale, Eduardo G. Khamis, and Arnaldo Gammal*

Instituto de Física, Universidade de São Paulo, 05508-090, São Paulo, Brazil
**gammal@if.usp.br*

We investigate the collision of oblique dark solitons in the two-dimensional supersonic nonlinear Schrödinger flow past two impenetrable obstacles. We numerically show that this collision is very similar to the dark solitons collision in the one-dimensional case. We observe that the collision is practically elastic and we measure the shifts of the solitons positions after their interaction. The numerical results are in agreement with hydrodynamical approximation and with an ansatz built with the Hirota method. These results are relevant for quantum fluids past an obstacle like the recent experiments with Bose gases and exciton-polaritons.

References

[1] E. S. Annibale and A. Gammal, *Interaction of oblique dark solitons in the two-dimensional nonlinear Schrödinger flow*, Phys. Lett. A **376**, pp. 46-50 (2011).
[2] E. G. Khamis and A. Gammal, *Hirota method for oblique solitons in the two-dimensional nonlinear Schrödinger flow*, http://arxiv.org/abs/1202.0697 (2012).

Stable skyrmions in *SU*(2) gauged Bose-Einstein condensates

Takuto Kawakami[1,*], Takeshi Mizushima[1], Muneto Nitta[2], and Kazushige Machida[1]

1. Okayama University, Okayama, Japan
2. Keio University, Kanagawa, Japan
**kawakami@mp.okayama-u.ac.jp*

The three-dimensional (3D) skyrmion in multi-component Bose-Einstein condensates (BECs) has attracted much attention. It is the topological object classified by the third homotopy group $\pi_3(S^3) = \mathbb{Z}$. However, its evidence has yet to be clarified in experiments because of the energetic instability. On the other hand, recently, BECs coupled with non-Abelian gauge fields have also attracted much attention in the sense of the spontaneous appearance of spatially modulated ground states. Here, we clarify that a 3D skyrmion spontaneously emerges as a "ground state" of BECs coupled with a realistic non-Abelian gauge field [1]. The gauge field is the 3D analogue of the Rashba type gauge field. In addition, we demonstrate that the textural crossover from the 3D to 1D or 2D skyrmion as squashing the 3D gauge field to be 1D or 2D forms, and provide the concept of the helical modulation as a unified understanding [2].

References

[1] T. Kawakami, T. Mizushima, M. Nitta, and K. Machida, arXiv:1204.3177.
[2] T. Kawakami, T. Mizushima, and K. Machida, Phys. Rev. A 84 011607(R).

Acoustic analog of the dynamical casimir effect

C. I. Westbrook*, D. Boiron, J. Ruaudel, R. Lopes, M. Bonneau,
J.-C. Jaskula, and G. Partridge

Laboratoire Charles Fabry, Institut d'Optique, CNRS/Université Paris-Sud, Palaiseau, France
**christoph.westbrook@institutoptique.fr*

Although we often picture the quantum vacuum as containing virtual quanta whose observable effects are only indirect, it is a remarkable prediction of quantum field theory that the vacuum can generate real particles when boundary conditions are suddenly changed [1]. Thus the 'dynamical Casimir effect' results in the spontaneous generation of photon pairs in an empty cavity whose boundaries are rapidly moving. Bose Einstein condensates are attractive candidates in which to study acoustic analogs to such phenomena [2], because their low temperatures promise to reveal quantum effects. Here we exhibit an acoustic analog to the dynamical Casimir effect by modulating the confinement of a Bose-Einstein condensate. We show that correlated pairs of Bogoliubov quanta, both phonon-like and particle-like, are excited by this modulation in a process that formally resembles parametric down conversion.

References

[1] G. Moore, J. Math Phys. **11**, 2679 (1970).
[2] I. Carusotto, R. Balbinot, A. Fabbri and A. Recati, Euro Phys J. D **56**, 391 (2010).

Simulating brane–anti-brane annihilation in Bose-Einstein condensates

Kenichi Kasamatsu[1,*], Hiromitsu Takeuchi[2], Makoto Tsubota[3], and Muneto Nitta[4]

1. Dept. of Phys., Kinki Univ., Higashi-Osaka, Japan
2. Graduate School of Integrated Arts and Sci., Hiroshima Univ., Higashi-Hiroshima, Japan
3. Dept. of Phys. and OCARINA, Osaka City Univ., Osaka, Japan
4. Dept. of Phys. and Res. and Educ. Center for Nat. Sci., Keio Univ., Yokohama, Japan
**kenichi@phys.kindai.ac.jp*

We study theoretically an analogous phenomenon of brane–anti-brane annihilation in two-component Bose-Einstein condensates. In brane cosmology, the Big Bang is hypothesized to occur by the brane–anti-brane annihilation and the instability of this system is explained by the concept of the 'tachyon condensation'. We construct an effective tachyon field theory for two-component BECs to explain the defect nucleation rate by a collision of the domain walls [1]. This defect creation process and subsequent relaxation dynamics can be understood as the phase ordering dynamics in a restricted lower dimensional space. We also discuss a new mechanism to create a 'vorton' (3D skyrmion) in the brane–anti-brane annihilation process [2]. All theoretical analyses are supported by the numerical simulations of the Gross-Pitaevskii equation.

References

[1] H. Takeuchi, *et al. Tachyon Condensation in Bose–Einstein Condensates*, arXiv:1205.2330.
[2] M. Nitta, *et al. Creating vortons and three-dimensional skyrmions from domain wall annihilation with stretched vortices in Bose-Einstein condensates*, Phys. Rev. A **85**, 053639 (2012).

Creation and detection of momentum entanglement with metastable helium

Michael Keller[1,2,*], Max Ebner[1,2], Mateusz Kotyrba[1,2], Mandip Singh[1], Johannes Kofler[1,3], and Anton Zeilinger[1,2]

1. Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austria
2. University of Vienna, Quantum Optics, Quantum Nanophysics, Quantum Information, Austria
3. Max-Planck Institute for Quantum Optics (MPQ), Garching, Germany
**michael.keller@univie.ac.at*

We present a possible scheme for creating and detecting entangled states in momentum space for neutral metastable Helium (He*) atoms.

Starting from a Bose-Einstein condensate (BEC) one can induce collisions between atoms to create entangled atom pairs. Very close to the original proposal by Einstein, Podolski and Rosen, those pairs are anti-correlated in their motional degree of freedom.

The possibility to detect individual He* atoms with a position resolved micro-channel plate (MCP) detector opens up the way for experiments to proof that the atoms are actually entangled, for example in a double double-slit experiment. We analyze requirements and restrictions for such an experiment, for example on detector resolution and source size, and show that it should be in principle achievable in our current setup.

The research was funded by the Austrian Science Fund (FWF): W1210 (CoQuS) and F4008 (FoQuS).

Momentum distribution of a trapped 1D Bose gas and Yang-Yang thermometry

N. J. van Druten[1,*], M. J. Davis[2], P. B. Blakie[3], A. H. van Amerongen[1], and K. V. Kheruntsyan[2]

1. Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands
2. The University of Queensland, School of Mathematics and Physics, Australia
3. Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, Dunedin, New Zealand
**N.J.vanDruten@uva.nl*

The one-dimensional (1D) Bose gas has emerged as a paradigm system in quantum many-body physics that allows unique opportunities for comparing experiment and theory. Experiments on atom chips allow direct measurements of the momentum distribution of a trapped 1D Bose gas [1]. We describe how these results can be compared to two theoretical approaches [2]. (i) stochastic projected Gross-Pitaevskii theory provides the first quantitative description of the full momentum distribution measurements, and (ii) exact solutions for the thermodynamics, obtained from the Yang-Yang equations (thermodynamic Bethe Ansatz) yield the root-mean-square width of the momentum distribution via the kinetic energy. We find that the fitted temperatures from both methods are in excellent agreement. These results open up interesting prospects for probing and characterizing more strongly correlated regimes via Yang-Yang kinetic-energy thermometry.

References

[1] A. H. van Amerongen *et al.*, *Yang-Yang thermodynamics on an atom chip*, Phys. Rev. Lett. **100**, 090402 (2008).
[2] M. J. Davis *et al.*, *Yang-Yang thermometry and momentum distribution of a trapped one-dimensional Bose gas*, Phys. Rev. A **85**, 031604(R) (2012).

Towards using atom chip technology to map and control solid-state devices

Samanta Piano[1,*], Bo Lu[1], Christian Koller[2], Jessica Maclean[1], Christopher Mellor[1], Mark Fromhold[1], and Peter Krüger[1]

1. School of Phyiscs and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK
2. Atominstitut, Vienna University of Technology, Stadionalle 2 1020, Vienna
**samanta.piano@nottingham.ac.uk*

Quantum technology embraces a broad range of emerging technologies which have witnessed remarkable progress in recent years, thanks to a steadily increasing degree of control of complex systems at the quantum level. Solid-state devices are the most promising candidates for scalable implementation of quantum electronics. On the other hand, ultra-cold atoms constitute the most sensitive and robust laboratory system to study and control coherent quantum dynamics, and find natural applications in quantum simulations and metrology. Recently, it has been demonstrated that a Bose-Einstein condensate (BEC), trapped near an atom chip, can be used as a field probe to give micron scale spatial resolution and very high magnetic field sensitivity. Our proposal aims to establish a two-way interface between cold atoms and solid-state systems in order to pursue a novel route towards hybrid quantum technology. This investigation will provide an important test-bed for the BEC field imaging technique, representing a breakthrough in the application of ultra-cold atomic systems for semiconductor based magnetic sensing. At the same time, it will provide an unprecedented level of both spatial and magnetic resolution to achieve a micro- and nano-scale characterisation of magnetic domains in semiconductors.

Quantum phase transitions and quench dynamics in sodium spinor BECs

Anshuman Vinit and Chandra Raman

School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
**craman@gatech.edu*

Spinor condensates present a unique arena for the study of quantum phase transitions and dynamical behavior close to critical points. In this work we report spontaneous spin domain formation in sodium Bose-Einstein condensates that are quenched, i.e. rapidly tuned, through a quantum phase transition from polar to antiferromagnetic phases. A microwave “dressing” field globally shifts the energy of the $m_F = 0$ level below the average of the $m_F = \pm 1$ energy levels, inducing a dynamical instability recently uncovered by our group [1]. We use local spin measurements to quantify the spatial ordering kinetics in the vicinity of the phase transition. For an elongated BEC, the instability nucleates small antiferromagnetic domains near the center of the polar condensate that grow in time along one spatial dimension. After a rapid nucleation and coarsening phase, the system exhibits long timescale non-equilibrium dynamics without relaxing to a uniform antiferromagnetic phase.

Reference

[1] E. M. Bookjans, A. Vinit, and C. Raman, “Quantum Phase Transition in an Antiferromagnetic Spinor Bose-Einstein Condensate”, Phys. Rev. Lett. 107, 195306 (2011).

Spin drag in a Bose gas

P. C. Bons[1,*], A. Groot[1], R. A. Duine[2], H. T. C. Stoof[2] and P. van der Straten[1]

1. Nanophotonics, Debye Institute, Utrecht University, The Netherlands
2. Institute for Theoretical Physics, Utrecht University, The Netherlands
**P.C.Bons@uu.nl*

Spin currents, which form the basis of spintronics, are subject to strong damping due to collisions between spin species. This phenomenon is known as spin drag. We have performed spin drag experiments for bosonic ultra-cold atoms in the condensed and non-condensed phase. We prepare an equal mixture of pseudo spin *up* and *down* atoms and apply a force on only one of the species. As a result a constant drift velocity between the spin species develops, which is a measure of spin drag. Close to the quantum phase transition to BEC we observe a strong increase of spin drag due to Bose enhancement acting as a precursor for Bose-Einstein condensation[1]. This is in agreement with recent theory. With increasing BEC fraction we expect spin drag to decrease due to the superfluid properties of the condensed phase. Our results pave the way for studies of transport properties of degenerate bosons that are very different from fermionic systems.

Reference

[1] S. B. Koller *et al.* "Spin drag in a Bose gas", arXiv :1204.6143 (2012).

Wave chaos and many-body dynamics in Bose-Einstein condensates

Iva Březinová[1,*], Lee A. Collins[2], Barry I. Schneider[3], Axel U. J. Lode[4], Alexej I. Streltsov[4], Ofir E. Alon[5], Lorenz S. Cederbaum[4], and Joachim Burgdörfer[1]

1. Institute for Theoretical Physics, Vienna University of Technology, Vienna, Austria
2. Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA
3. Physics Division, National Science Foundation, Arlington, Virginia, USA
4. Theoretische Chemie, Physikalisch-Chemisches Institut, Universtität Heidelberg, Heidelberg, Germany
5. Department of Physics, University of Haifa at Oranim, Tivon, Israel
**iva.brezinova@tuwien.ac.at*

We show that the solutions of the Gross-Pitaevskii equation (GPE) exhibit wave chaos for a wide range of external potentials including disorder potentials and periodic lattices. In the presence of wave chaos two almost identical wave functions become orthogonal during time evolution by developing random fluctuations. We find a connection between wave chaos and the depletion of the BEC which reveals that wave chaos marks the breakdown of the mean-field description within the GPE. Wave chaos in the GPE can thus be utilized to identify many-body effects. To quantify many-body effects we employ the multiconfigurational time-dependent Hartree for bosons method (MCTDHB). Our results indicate that even in systems where previously good agreement of GPE predictions with experiment has been found, interesting many-body dynamics is present and has so far not been fully appreciated.

Adolescence of quantum-degenerate strontium

Simon Stellmer[1,*], Benjamin Pasquiou[1], Rudolf Grimm[1,2], and Florian Schreck[1]

1. Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria
2. Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria
**simon.stellmer@oeaw.ac.at*

The first BECs of strontium were created three years ago. This was achieved with the isotope ^{84}Sr, and degeneracy of the other three stable isotopes followed soon afterwards. Since then, we have expanded our capabilities to prepare for future experiments, including the study of novel schemes of quantum simulation, creation of alkali-alkaline earth molecules, and precision measurements. In particular, we have improved the number of atoms in the ^{84}Sr BEC to above 10^7, created deeply-degenerate Fermi gases, and generated five different double-degenerate mixtures of both fermions and bosons. We have established a scheme to manipulate and detect the spin states of the fermionic isotope ^{87}Sr with high fidelity, and performed spectroscopy in the triplet system. Furthermore, we have implemented an optical lattice, which we used to create ultracold Sr_2 molecules in the electronic ground state (see companion poster by B. Pasquiou). Our efforts culminate in the development of a novel optical cooling scheme (see companion contribution by F. Schreck). These studies show the maturation of experimental techniques for degenerate gases of strontium, leading up to unique applications that are anticipated in the near future. A selection of these studieswill be presented on the poster.

Bose gases Th-070

Non-equilibrium behaviour of Bose-Einstein Condensates

Robert P. Smith*, Alex L. Gaunt, Richard J. Fletcher, Stuart Moulder, Scott Beattie, and Zoran Hadzibabic

Cavendish Lab., University of Cambridge, UK
**rps24@cam.ac.uk*

Using the ability to tune the interaction strength in a harmonically trapped ultracold Bose gas of ^{39}K atoms we study non-equilibrium phenomena in Bose-Einstein Condensates.

(1) By quenching the strength of interactions in a partially condensed Bose gas we create a “super-saturated” vapor which has more thermal atoms than it can contain in equilibrium. Subsequently, the number of condensed atoms (N_0) grows even though thetemperature (T) rises and the total atom number decays. We show that the non-equilibrium evolution of the system is isoenergetic and for small initial N_0 observe a clear separation between T and N_0 dynamics, thus explicitly demonstrating the theoretically expected “two-step” picture of condensate growth. For increasing initial N_0 values we observe a crossover to classical relaxation dynamics [1].

(2) At low interaction strengths we show that decoupling from the thermal bath can lead to “superheated” condensates which survive at temperatures up to almost twice the equilibrium transition temperature. We study both how this phenomena depends on theinteraction strength and also the subsequent dynamics of the condensate decay which can be induced by rapidly increasing the interaction strength.

Reference

[1] R. P. Smith, S. Beattie, S. Moulder, R. L. D. Campbell and Z. Hadzibabic, arXiv:1112.4457 (2012).

The effect of light assisted collisions on matter wave coherence in superradiant Bose-Einstein condensates

Nir S. Kampel[1,*], Axel Griesmaier[1,2], Mads P. Hornbak Steenstrup[1],
Franziska Kaminski[1], Eugene S. Polzik[1], and Jörg H. Müller[1]

1. Niels Bohr Institute, Copenhagen University, 2100 Copenhagen Ø, Denmark
2. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany
**nir.kampel@nbi.dk*

Elastic Rayleigh scattering of photons from atoms in a Bose-Einstein condensate (BEC) creates long-lived ripples in the density distribution of the atomic cloud. Bosonic stimulation leads to a positive feedback mechanism enhancing the formation of a matter-wave grating. This directed Rayleigh scattering is well known as Rayleigh superradiance, and recently it has been shown to depend asymmetrically on the sign of the pump light detuning [1]. Here we experimentally demonstrate this detuning asymmetry in the threshold, and present a model that explains the source of the surprising asymmetry. We attribute the threshold increase to excitation onto repulsive molecular potentials followed by emission of resonant photons. The matter-wave coherence is strongly inhibited by those resonant photons [2].

References

[1] L. Deng, M. G. Payne, and E. W. Hagley, *Electromagnetic Wave Dynamics in Matter-Wave Superradiant Scattering*, Phys. Rev. Lett. **104**, 050402 (2010).
[2] N. S. Kampel, A. Griesmaier, M. P. Hornbak Steenstrup, K. Kaminski, E. S. Polzik, and J. H. Müller *Effect of Light Assisted Collisions on Matter Wave Coherence in Superradiant Bose-Einstein Condensates*, Phys. Rev. Lett. **108**, 090401 (2012).

Nonequilibrium Thermo Field Dynamics approach to thermal process for one dimensional Bose gas in optical lattice

Yukiro Kuwahara, Yusuke Nakamura, and Yoshiya Yamanaka

Department of Electronic and Photonic Systems, Waseda University, Tokyo, Japan
**a.kuwahara1224@asagi.waseda.jp*

The system of cold neutral atomic gas has recently attracted attentions, because there the time scales of thermal processes are sufficiently slow to observe various nonequilibrium phenomena. Thermo Field Dynamics (TFD) formalism is one of the quantum field theories for thermal situations [1]. The non-Markovian quantum transport equations for the gases have been derived in nonequilibrium TFD [2, 3]. We here extend our previous work to the system with a time-dependent external field. For this purpose, we apply the nonequilibrium TFD to the one dimensional system of cold neutral atomic Bose gas confined by a combined harmonic and optical lattice potentials. We investigate the thermal process for the system after a sudden displacement of the former potential, analyzing the quantum transport equation numerically.

References

[1] H. Umezawa, *Advanced Field Theory - Micro, Macro, and Thermal Physics* (AIP, New York, 1993).
[2] Y. Nakamura, T. Sunaga, M. Mine, M. Okumura, Y. Yamanaka, Ann. Phys. (N.Y.) **325**, 426 (2010).
[3] Y. Nakamura and Y. Yamanaka, Ann. Phys. (N.Y.) **326**, 1070 (2011).

Instability in the Riemann problem of the two-fluid hydrodynamic equations for Bose-Einstein condensate

Vladimir I. Tsurkov

Vavilov str., 40, Moscow, 119333, Russia
tsur@ccas.ru

We consider the time dependent two-fluid hydrodynamic equations with one spatial coordinate x for the degenerate ideal Bose gas. The equation of state is $p = BS^{5/3}$, where p is the pressure, S is the entropy per unit volume (B = *const*). We obtain two splitting pair of equations. The second set is

$$\partial v_S / \partial t + v_S \partial v_S / \partial x = 0$$

$$\partial R / \partial t + R \partial v_S / \partial x + v_S \partial R / \partial x = 0$$

where v_S is the superfluid velocity, $R = \rho - AS$, ρ is the density (A = *const*). The Riemann problems with the initial values $\rho(0,x) = \rho_0$, $S(0,x) = S_0$ $(\rho_0, S_0 - const)$ and $v_S(0,x) = v_1(x < 0)$, $v_S(0,x) = v_2(x > 0)$, $v_1 > v_2$ lead to an unstable solution where the density becomes unbounded by analogy to [1], [2], [3]. Although equation of two-component hydrodynamic is not applicable to ideal degenerated Bose gas, obtained solutions may be treated as limit ones for non-ideal gas.

References
[1] V. I. Tsurkov, Comput. Math. Math. Phys. **11**, 488 (1971).
[2] V. I. Tsurkov, *Majorant Catastrophe of Eulerian Gas Dynamics Equations for Bosons*, Felicity Press, USA (1998).
[3] V. I. Tsurkov, J. Low Temp. Phys. **138**, 717 (2005).

Mixtures of strongly and weakly correlated Bose gases

Miguel Angel Garcia-March[1,*], Thomas Fogarty[1], and Thomas Busch[1,2]

1. University College Cork, Cork, Ireland
2. Quantum Systems Unit, Okinawa Institute of Science and Technology, Okinawa, Japan
**magmarch@phys.ucc.ie*

We present an exact many body description of small mixtures of two ultracold bosonic species in a one-dimensional trap that permit us to study the case in which they are in different correlation regimes. Within this framework we obtain the criteria for phase separation when either both species form Bose-Einstein condensates (BEC) or when one of them is in the Tonks-Girardeau limit. For the second case we compare our description with the semiclassical mean-field description, which is known to accurately describe the density distribution [1]. Finally, we use our model to describe dynamics as well as quantum correlations between both species. The atoms in the Girardeau gas act as impurities submerged in the BEC, and we investigate the effects the condensed environment has on the Girardeau gas as a function of the interspecies scattering strength.

Reference
[1] E. B. Kolomeisky, T. J. Newman, J. P. Straley, and X. Qi, *Low-Dimensional Bose Liquids: Beyond the Gross-Pitaevskii Approximation*, Phys. Rev. Lett. **85**, pp. 1146 (2000).

Decay of a superfluid current of ultra-cold atoms in a toroidal trap

Amy C. Mathey[1,*], Charles W. Clark[2], and L. Mathey[1]

1. Zentrum für Optische Quantentechnologien and Institut für Laserphysik,Universität Hamburg, 22761 Hamburg, Germany
2. Joint Quantum Institute, National Institute of Standards and Technology & University of Maryland, Gaithersburg, MD 20899
**amathey@physnet.uni-hamburg.de*

Using a numerical implementation of the truncated Wigner approximation, we simulate the experiment reported by Ramanathan *et al.* in Phys. Rev. Lett. **106**, 130401 (2011), in which a Bose-Einstein condensate is created in a toroidal trap and set into rotation via a Gauss-Laguerre beam. A potential barrier is then placed in the trap to study the decay of the superflow. We find that the current decays via thermally activated phase slips, which can also be visualized as vortices crossing the barrier region in radial direction. Adopting the notion of critical velocity used in the experiment, we determine it to be lower than the local speed of sound at the barrier. This result is in agreement with the experimental findings, but in contradiction to the predictions of the Gross-Pitaevskii equation. This emphasizes the importance of thermal fluctuations in the experiment.

Effect of disorder in two-dimensional Bose gases

B. Allard[1], T. Plisson[1], M. Holzmann[2,3], G. Salomon[1], A. Aspect[1], P. Bouyer[4], and T. Bourdel[1,*]

1. Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ Paris-Sud, 2, Palaiseau, France
2. LPTMC, CNRS, Université P. et M. Curie, Paris, France
3. LPMMC, Université Grenoble 1,CNRS, Grenoble, France
4. LP2N, Univ Bordeaux 1, IOGS, CNRS, Talence, France
**thomas.bourdel@institutoptique.fr*

Interacting 2D Bose gases undergo a thermal phase transition to a superfluid phase at low temperature. It is a Berezinskii-Kosterlitz-Thouless type transition in which the interactions between particles are playing a crucial role. We have studied this transition through the emergence of phase coherence in the momentum distribution [1].

The influence of disorder on the 2D superfluid transition is an important open problem in condensed matter physics. It is relevant to a variety of systems such as helium films, thin metallic films, or even high temperature superconductors. Experimentally we study how microscopically correlated disorder changes the coherence properties of the 2D Bose gas close to the superfluid transition as a function of both temperature and disorder strength [2]. Our study is an experimental realization of the dirty boson problem in a well controlled atomic system suitable for quantitative analysis.

References

[1] T. Plisson, *et al.*, *Coherence properties of a 2D trapped Bose gas around the superfluid transition*, Phys. Rev. A **84**, 061606(R) (2011).
[2] B. Allard, *et al.*, *Effect of disorder close to the superfluid phase transition in a two-dimensional Bose gas*, Phys. Rev. A **85**, 033602 (2012).

Anisotropy of sound velocity in a dipolar Bose-Einstein Condensate

G. Bismut, L. Vernac, B. Pasquiou, E. Marechal, P. Pedri, B. Laburthe-Tolra, and O. Gorceix*

Laboratoire de Physique des Lasers, CNRS/Université Paris-Nord, Villetaneuse, France
**olivier.gorceix@univ-paris13.fr*

We provide an experimental demonstration of a new dipolar effect in a dilute quantum fluid using Raman-Bragg spectroscopy to measure the excitation spectrum of a trapped spin-polarized degenerate quantum gas made chromium atoms (Cr-BEC). Spectra are recorded for orthogonal orientations of the spin with respect to the trap axes. The dipolar interactions between the atoms induce an anisotropy of the sound velocity inside the BEC. As we span the frequency domain from the phonon range up to the single-particle range, the excitation energy is clearly different for parallel and perpendicular orientations of the excitation wave-vector with respect to the spin. This work complements previously published studies of the collective excitations of the chromium BEC [1]. We plan to use this scheme to deepen our understanding of the magnetization processes in the multicomponent spin-3 chromium condensate with special interest for 2D and 1D systems [2, 3].

References

[1] G. Bismut *et al.*, Phys. Rev. Lett. **105**, 040404 (2010).
[2] B. Pasquiou *et al.*, Phys. Rev. Lett. **106**, 255303 (2011).
[3] B. Pasquiou *et al.*, Phys. Rev. Lett. **108**, 045307 (2012).

Magnetic properties of a dipolar BEC loaded into a 3D optical lattice

A. Chotia, A. de Paz, E. Maréchal, P. Pedri, L. Vernac, O. Gorceix, and B. Laburthe-Tolra

Laboratoire de Physique des Lasers, UMR 7538 CNRS, Université Paris Nord, Villetaneuse, France

We have observed how magnetization changing collisions, dipolar relaxation, are dramatically modified by the confining potential when a chromium BEC is confined into a 3D optical lattice. The interplay between internal (atomic) and external (lattice) degrees of freedom controls the two body inelastic collision process. In a 3D lattice, relaxation of atoms initially in the highest Zeeman state is almost suppressed. However, we observe resonances corresponding to particular combination of Zeeman energy and vibrational lattice spacing. We performed the spectroscopy of these resonances for two orientations of the magnetic field and observed a direct signature of the anisotropy of the dipolar interaction. By focusing our attention on the lowest energy excitation peak we found that its shape is sensitive to the interaction energy in each lattice site, and that it can be used as a global probe of the mean site occupation distribution. With such a probe, we studied how the mean site occupation distribution changes as we vary the loading ramp speed of the lattice. Finally we studied lattice magnetism in the ground state of a 3D optical lattice and observed a spontaneous depolarization of the BEC when the onsite interactions overwhelm the Zeeman effect.

Vortices in rotating dipolar Bose-Einstein condensates confined in annular potentials

E. Ö. Karabulut[1,3,*], F. Malet[1], G. M. Kavoulakis[2], and S. M. Reimann[1]

1. Mathematical Physics, Lund Institute of Technology, P.O. Box 118, SE-22100 Lund, Sweden
2. Technological Educational Institute of Crete, P.O. Box 1939, GR-71004, Heraklion, Greece
3. Physics Department, Faculty of Science, Selcuk University, TR-42075, Konya, Turkey
**elife.karabulut@matfys.lth.se, eoyildirim@selcuk.edu.tr*

Low-dimensional confinements offer the opportunity to study the effects of dipolar interaction without instability problems caused by the head-to-tail alignment of dipoles in three dimensions [1]. To investigate the anisotropic character of the interaction, we consider a rotating dipolar Bose-Einstein condensate confined in an annular trap for an arbitrary orientation of the dipoles with respect to their plane of motion [2]. Within the mean-field approximation, as previously studied for a quasi-two-dimensional elliptical potential [3], we find that the system exhibits different vortex structures depending on the polarization angle of the dipoles and on the relative strength between the dipolar and the contact interactions.

References
[1] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau, Rep. Prog. Phys. **72**, 126401 (2009).
[2] S. Zöllner, G. M. Bruun, C. J. Pethick, and S. M. Reimann, Phys. Rev. Lett. **107**, 035301 (2011); M. Abad, M. Guilleumas, R. Mayol, M. Pi, and D. M. Jezek, Phys. Rev. A **81**, 043619 (2010).
[3] F. Malet, T. Kristensen, S. M. Reimann, and G. M. Kavoulakis, Phys. Rev. A **83**, 033628 (2011).

Towards a two-species quantum degenerate gas of ^{6}Li and ^{133}Cs

Rico Pires*, Juris Ulmanis, Marc Repp, Robert Heck, Eva Kuhnle, and Matthias Weidemüller

Physics Institute and Heidelberg Center for Quantum Dynamics, University of Heidelberg, Germany
**pires@physi.uni-heidelberg.de*

This poster will present the design and the current status of our experimental apparatus for the all-optical production of a quantum degenerate mixture of Li and Cs atoms.

From this starting point, ultracold LiCs molecules can be created via Feshbach association and subsequent Stimulated Raman Adiabatic Passage, which transfers the molecules to the ground state. In this state the molecules exhibit a very large dipole moment of 5.5 Debye [1], which enables the investigation of dipolar physics in ultracold gases.

Additionally, this mixture represents an excellent choice for the investigation of mixed species Efimov physics, due to the favorable scaling factor of 4.88 [2], which should enable us to observe a large series of Efimov resonances.

References
[1] J. Deiglmayr, A. Grochola, M. Repp, O. Dulieu, R. Wester, and M. Weidemüller, " Permanent dipole moment of LiCs in the ground state", Phys. Rev. A 82, 032503 (2010).
[2] J. P. D'Incao and B. D. Esry, "Enhancing the observability of the Efimov effect in ultracold atomic gas mixtures", Phys. Rev. A 73, 030703 (2006).

Anisotropic spontaneous four-wave mixing of two colliding dipolar Bose-Einstein condensates

Guangjiong Dong*, Jieli Qin, and Weiping Zhang

State Laboratory of Precision Spectroscopy, East China Normal University, Shanghai, China
**dong.guangjiong@gmail.com*

The development of quantum matter wave optics studying nonclassical states of matter waves has benefited from analogy of conventional Bose-Einstein condensates (BEC) to nonlinear Kerr media. Whereas, dipolar BECs are like asymmetric nonlocal nonlinear media, and thus can be used for studying quantum matter wave optics beyond Kerr nonlinear quantum optics. Now,we investigate spontaneous four-wave mixing of two colliding dipolar BECs. A deformed halo of the scattered dipoles leads to directional correlated dipolar pairs, which could be controlled with the alignment of the dipoles. Further analysis shows that back-to-back dipole pairs have anisotropic Einstein – Podolsky – Rosen correlation, which can be used in quantum metrology and quantum mechanics foundation test.

Dipolar gases Th-082

Anisotropic features of dipolar Fermi gases

Yuki Endo[1,*], Tetsuro Nukuni[2], and Yoji Ohashi[1]

1. Department of Physics, Faculty of Science, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo, Japan, 162-8601
2. Department of Physics, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

Since the realization of BEC of ^{52}Cr atomic gases with large magnetic dipole moments [1], dipolar quantum gases have attracted much attention. Recently, experimentalists have tried to produce heteronuclear polar molecules with large electric dipole moments. The anisotropic and long-range nature of a dipole-dipole interaction leads to various properties. Especially, dipolar fermi gases have two fundamental phenomena, i.e., fermi surface deformation [2] and superfluid pairing [3]. The former is induced by the anisotropic nature of the dipole-dipole interaction, which affects the the equilibrium and the dynamic properties, as well as the stability of the system. Anisotropic dipole-dipole interaction also induces the superfluid phase transition. Several theoretical studies have predicted an anisotropic BCS pairing associated with the dipole-dipole interaction.

In this work, we study the properties of dipolar fermi gases. Including the deformation of the Fermi surface, we clarify the characteristic features caused by anisotropic dipole-dipole interaction.

References

[1] Axel Griesmaier, Jörg Werner, Sven Hensler, Jürgen Stuhler, and Tilman Pfau, Phys. Rev. Lett. **94**, 160401 (2005).
[2] Takahiko Miyakawa, Takaaki Sogo, and Han Pu, Phys. Rev. A **77**, 061603 R (2008).
[3] M. A. Baranov, M. S. Mar'enko, Val. S. Rychkov, and G. V. Shlyapnikov, Phys. Rev. A **66**, 013606 (2002).

Thermodynamics of the unitary Fermi gas and pairing from 3D to 2D

Mark J.-H. Ku*, Ariel T. Sommer†, Lawrence W. Cheuk, Waseem S. Bakr, and Martin W. Zwierlein

Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, MIT, Cambridge, Massachusetts, USA
**mku@mit.edu*
† atsommer@mit.edu

We measure the equation of state of a Fermi gas with unitary interactions [1]. We use a novel method that requires no fit or external thermometer. The thermodynamic signatures of the superfluid phase transition are observed for the first time, revealed in the compressibility, the chemical potential, the entropy, and the heat capacity. Our precision measurement of the thermodynamics provide a benchmark for many-body theories on strongly interacting fermions, relevant for problems ranging from high-T_c superconductivity to the equation of state of neutron stars. In a separate experiment, we study the binding energy of fermion pairs in the crossover from three to two dimensions [2]. Dimensionality is tuned by varying the depth of a one-dimensional optical lattice imposed on a gas of ^{6}Li atoms. The binding energy is measured as a function of lattice depth and interaction strength and compared with theoretical predictions.

References

[1] M. Ku *et al.*, Science **335**, 563 (2012).
[2] A. Sommer *et al.*, Phys. Rev. Lett. **108**, 045302 (2012).

Spin-orbit-coupled ultracold atomic gases

Xia-Ji Liu[1,*], Lei Jiang[2], B. Ramachandran[2], Han Pu[2], and Hui Hu[1]

1. Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne, Australia
2. Department of Physics and astronomy, and Rice Quantum Institute, Rice University, Houston, Texas, USA
**xiajiliu@swin.edu.au*

Ultracold atoms have been proven to be an ideal table-top system to reveal novel states of quantum matter. The latest development of generating a synthetic spin-orbit coupling (SOC) in ultracold atoms has created a new frontier that is endowed with a strong interdisciplinary character and a close connection to new functional materials - topological insulators. Here, we report our theoretical work on spin-orbit-coupled ultracold atomic gases. For Fermi gases, we predict a new anisotropic state of matter which consists of exotic quasi-particles with anisotropic effective mass. In the superfluid phase, these quasi-particles exhibit salient features in the momentum distribution, single-particle spectral function and spin structure factor, easily detectable in current experiments [1]. For Bose-Einstein condensates, we show that the interplay between the SOC and inter-atomic interaction leads to a very rich phase diagram, with each phase featuring a distinct spin-texture pattern and symmetry class [2].

References

[1] H. Hu, L. Jiang, X.-J. Liu and H. Pu, Phys. Rev. Lett. **107**, 195304 (2011).
[2] H. Hu, B. Ramachandhran, H. Pu, and X.-J. Liu, Phys. Rev. Lett. **108**, 010402 (2012).

Solitons from BCS to BEC

Robin G. Scott[1,*], Franco Dalfovo[1], Lev P. Pitaevskii[1,2], and Sandro Stringari[1]

1. INO-CNR BEC center, Università di Trento, Via Sommarive 14, I-38123 Povo, Italy
2. Kapitza institute for physical problems, ul. Kosygina 2, 119334 Moscow, Russia
**scott@science.unitn.it*

We perform time-dependent simulations of three-dimensional fermionic superfluids across the Bose-Einstein condensate to Bardeen-Cooper-Schrieffer (BEC-BCS) crossover by solving the Bogoliubov-de Gennes (BdG) equations. The BdG equations describe fermionicquasiparticles which are essential for simulating topological excitations such as solitons [1, 2] and vortices, since these objects have a width of the order of the inverse Fermi wavevector and contain localised Andreev states which play an important role in their dynamics [2]. Hence the calculations are extremely heavy and must be run in parallel on a supercomputer. Our latest simulations model the decay of solitons into vortices via the snake instability. We find that the timescale of the decay varies little between the unitary and BEC regimes, but becomes much slower in the BCS regime. The snake instability is also suppressed for grey solitons moving at a velocity close to the pair-breaking threshold.

References

[1] R. G. Scott, F. Dalfovo, L. P. Pitaevskii and S. Stringari, *Dynamics of dark solitons in a trapped superfluid Fermi gas*, Phys. Rev. Lett. **106**, 185301 (2011).
[2] R. G. Scott, F. Dalfovo, L. P. Pitaevskii, S. Stringari, O. Fialko, R. Liao and J. Brand, *The decay and collisions of dark solitons in superfluid Fermi gases*, New J. Phys. **14**, 023044 (2012).

Quantum Monte-Carlo algorithm for FeAs-superconductors

Vladimir Kashurnikov and Andrey Krasavin*

National Research Nuclear University MEPhI, Moscow, Russia
**avkrasavin@gmail.com*

The new World-Line Quantum Monte-Carlo Algorithm for the study of FeAs-based superconductors is suggested. Properties of these superconductors can be described within the two-orbital model [1], the minimal model taking into account the crystal structure of FeAs-layers, and practically being the limit of complexity for realization of algorithms on numerical modeling of new superconducting compounds. The suggested coding of electron states allows of considering in the new algorithm the complex terms describing pair electron transitions between orbitals. The developed algorithm can be used for the study of the influence of superconducting cluster size, temperature, and doping on local and non-local properties of FeAs-compounds.

Reference

[1] M. Daghofer, A. Moreo, J. A. Riera, E. Arrigoni, D. J. Scalapino, and E. Dagotto, “Model for the Magnetic Order and Pairing Channels in Fe Pnictide Superconductors”, Phys. Rev. Lett. **101**, 237004 (2008).

Precision studies of the contact parameter in a unitary Fermi gas

Sascha Hoinka[1], Marcus Lingham[1], Kristian Fenech[1], Hui Hu[1], Chris J. Vale[1,*],
Joaquín E. Drut[2], and Stefano Gandolfi[2]

1. Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne 3122, Australia
2. Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545-0001, USA
**cvale@swin.edu.au*

Ultracold Fermi gases near Feshbach resonances provide an unparalleled setting to obtain a precise understanding of highly correlated many-body systems. These systems, characterised by short-range interactions and large scattering lengths, are challenging to describe theoretically and various approximate methods have been employed to make calculations tractable. Reliable experimental benchmarks are therefore a key requirement and progress is now demanding accuracies at the level of one percent. Here, we report on our precision experimental measurements of the dynamic and static structure factors of strongly interacting Fermi gases and the use of these to make the most precise determination of Tan's universal contact parameter [1] in a unitary Fermi gas. Our results are compared with different theoretical predictions including Quantum Monte Carlo and many-body t-matrix methods. We also present our progress towards obtaining the homogeneous contact from measurements on a trapped gas.

Reference

[1] S. Tan, *Energetics of a strongly correlated Fermi gas*, Ann. Phys. **323**, 2952 (2008).

Trapping and manipulation of a mixture of fermionic ultra-cold ^{6}Li and ^{40}K atoms in an optical dipole trap

Franz Sievers*, Diogo Fernandes, Norman Kretzschmar, Daniel Suchet,
Frédéric Chevy, and Christophe Salomon

Laboratoire Kastler Brossel, CNRS, UPMC, Ecole Normale Supérieure, 75005 Paris, France
**franz.sievers@lkb.ens.fr*

We are developing a new apparatus dedicated to the cooling and trapping of mixtures of fermionic Lithium and Potassium atoms. The experiment will focus on low dimensional systems that can be achieved using tight optical confinement to freeze some atomic degrees of freedom. In this regime, we expect to observe phenomena equivalent to the ones observed in condensed matter systems as well as new exotic phases of matter.

We report on recent results, including D1 sub-Doppler cooling of fermionic Lithium, the performance of the magnetic transport from the MOT chamber to the science cell and the improved vacuum system.

Fermi superfluid in a Kagome optical lattice

Chika Sato[1], Daisuke Yamamoto[2], Shunji Tsutiya[1], and Tetsuro Nikuni[1]

1.Department of Physics, Faculty of Science, Tokyo University of Science,Tokyo 162-8601, Japan
2. Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan

Since the experimental realization by the Berkeley group[1], Kagome optical lattice have been of great interest given the possibility to simulate geometrically frustrated systems and to realize exotic phases such as quantum spin liquids[2] and flat band ferromagnets[3]. We study the attractive Hubbard model in the Kagome lattice in order to explore the superfluid phases in this lattice geometry. We calculate the superfluid order parameter and collective modes within the mean-field theory and strong coupling spin-wave analysis. We find that the superfluid order parameter is remarkably enhanced due to infinitely large density of states associated with the flat band. We discuss the possibility of supersolid phases when finite superflow is imposed.

References
[1] Gyu-Boong Jo, *et al.*, *Ultracold Atoms in a Tunable Optical Kagome Lattice*, Phys. Rev. Lett. **108**, 045305 (2012).
[2] L. Balents, *Ultracold Atoms in a Tunable Optical Kagome Lattice*, Nature **464**, 199 (2010).
[3] Hal Tasaki, *Ferromagnetism in the Hubbard Model with Degenerate Single-Electron Grand State*, Phys. Rev. Lett. **69**, 1608 (1992).

Strong-coupling effects on single-particle properties of a *p*-wave superfluid

Daisuke Inotani[1,*], Manfred Sigrist[2], and Yoji Ohashi[1]

1. Department of Physics, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
2. Institut für Theoretische Physik, ETH Zürich,CH-8093 Zürich, Switzerland
**dinotani@rk.phys.keio.ac.jp*

We investigate strong-coupling effects on single-particle properties of a *p*-wave atomic Fermi superfluid, induced by a *p*-wave Feshbach resonance. This type of pairing interaction has been recently observed in ^{40}K [1] and ^{6}Li [2] Fermi gases. Because of the splitting of three channels (p_x, p_y, and p_z) of a *p*-wave Feshbach resonance by a magnetic dipole-dipole interaction [1], the phase transition from the p_x-wave pairing state to the $p_x + ip_y$ -wave state hasbeen predicted below the superfluid phase transtion temperature T_c [3]. Near this (p_x) - $(p_x + ip_y)$ -phase transition temperature ($T_{p_x+ip_y}$), pairing fluctuations associated with the non-condensed p_y- and p_z-component are expected to become strong even below T_c. Including these fluctuation effects in a consistent manner, we calculate single-particle density of states, as well as the spectral weight, in a one-component Fermi gas with a *p*-wave interaction below T_c. In this poster presentation, we show how the *p*-wave pairing fluctuations affect the single-particle properties near $T_{p_x+ip_y}$.

References
[1] C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Phys. Rev. Lett. **90**, 053201 (2003).
[2] J. Zhang *et al.*, Phys. Rev. A **70**, 030702(R) (2004).
[3] V. Gurarie, L. Radzihovsky, and A. V. Andreev, Phys. Rev. Lett. **94**, 230403 (2005).

Strong-coupling effects on photoemission spectra of two-dimensional Fermi gases in the BCS-BEC crossover

Ryota Watanabe[1,*], Shunji Tsuchiya[2,3], and Yoji Ohashi[2]

1. Department of Physics, Faculty of Science and Technology, Keio University, Yokohama, Japan
2. Department of Physics, Faculty of Science, Tokyo University of Science, Tokyo, Japan
3. Research and Education Center for Natural Sciences, Keio University, Yokohama, Japan
**rwatanab@rk.phys.keio.ac.jp*

We study single-particle properties and strong-coupling effects in a trap of two-dimensional Fermi gases. Including pairing fluctuations within a T-matrix approximation, as well as a trap potential within the local density approximation, we self-consistently determine the superfluid transition temperature T_c and Fermi chemical potential above T_c. Using these, we calculate the local density of states (LDOS), local spectral weight, and photoemission spectra above T_c. We show that the pseudogap inhomogeneously appears in LDOS near T_c, and it remains up to $T \sim T_F$ in the crossover region. We also demonstrate how the pseudogap phenomenon affects temperature dependence of the photoemission spectra above T_c in the entire BCS-BEC crossover region. Our results would be useful for understanding low-dimensional strong-coupling effects in the BCS-BEC crossover regime of a trapped Fermi gas.

Thermalization process of the nonequilibrium initial distribution for two-component Fermi gas in nonequilibrium Thermo Field Dynamics

Yusuke Nakamura*, Yukirou Kuwahara, and Yoshiya Yamanaka

Department of Electronic and Photonic Systems, Waseda University, Tokyo, Japan
**nakamura@aoni.waseda.jp*

The thermalization process for the system of two-component Fermi gas is investigated in the framework of nonequilibrium Thermo Field Dynamics (TFD) [1]. In nonequilibrium TFD, which is a real-time canonical formalism of quantum field theory, a mixed state expectation in the density matrix formalism is replaced by an expectation of the pure state vacuum, called thermal vacuum. A number distribution is introduced as an unknown time-dependent parameter, and a self-consistent renormalization condition [2] derives its equation, *i.e.*, the quantum transport equation [3]. In this poster, we derive the quantum transport equations for the system of weak interacting two-component Fermi gas using nonequilibrium TFD, and illustrate the thermalization process of the nonequilibrium initial distribution. Our transport equation is not based on the phase-space distribution function, but follows from the appropriate choice of the representation space which is essential for quantum field theory.

References

[1] H. Umezawa, "*Advanced Field Theory — Micro, Macro, and Thermal Physics*" (AIP, New York, 1993).
[2] H. Chu and H. Umezawa, Int. J. Mod. Phys. A, **10**, 1693 (1995).
[3] Y. Nakamura *et al.*, Ann. Phys. (N. Y.) , 426 (2010); *ibid.* **326**, 2070 (2011).

Instability of superfluid Fermi gases caused by bosonic excitations

Hiroki Yamamura[1,*] and Daisuke Yamamoto[2]

1. Department of Physics, Waseda University, Shinjuku, Tokyo 169-8555, Japan
2. Condensed Matter Theory Laboratory, RIKEN, Wako, Saitama 351-0198, Japan
**yamamura@kh.phys.waseda.ac.jp*

We study the instability of the superflow in three-dimensional superfluid Fermi gases. In the previous work [1], the superfluid critical velocity is determined by the fermionic single-particle excitations in the weak-coupling BCS regime and by the bosonic collective excitations in the strong-coupling BEC regime. However, even after fermionic excitations occur, stable gapless superfluid states can exist in three-dimensional systems. We therefore analyzed the critical velocity of the superflow taking into account the gapless superfluid states. As a result, we found that even in the BCS regime, bosonic collective excitations cause the instability of the superflow before the gap function becomes zero.

Reference

[1] R. Combescot, M. Yu. Kagan and S. Stringari, Phys. Rev. A **74**, 042717 (2006).

Spin susceptibility and fluctuation effects in an ultracold Fermi gas

Takashi Kashimura[1,*], Ryota Watanabe[1], and Yoji Ohashi[1,2]

1. Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
2. CREST, JST, 4-1-8 Honcho, Saitama 332-0012, Japan
**t.kashimura@a3.keio.jp*

We investigate strong-coupling corrections to the spin susceptibility in an ultracold Fermi gas with an attractive interaction. In a population imbalanced system, the BCS-BEC crossover theory developed by Nozières and Schmitt-Rink (NSR) [1] is known to unphysically give the negative value of spin susceptibility in the crossover region [2,3]. This problem still remains even in the *T*-matrix theory. To overcome this serious problem, we extend these theories to properly include higher order fluctuation effects. The resulting extended *T*-matrix theory correctly gives the positive value of spin susceptibility in the entire BCS-BEC crossover region. We also show that our results well agree with the experimental results on spin susceptibility, measured by *in situ* imaging of dispersive speckle patterns [4].

References

[1] P. Nozières and S. Schmitt-Rink, J. Low Temp. Phys. **59**, 195 (1985).
[2] X.-J. Liu and H. Hu, Europhys. Lett. **75**, 364 (2006).
[3] M. M. Parish, *et al.*, Nat. Phys. **3**, 124 (2007).
[4] C. Sanner, *et al.*, Phys. Rev. Lett. **106**, 010402 (2011).

P-orbital physics in an optical chequerboard lattice

T. Kock, A. Ewerbeck, G. Wirth, M. Ölschläger, and A. Hemmerich

Institut für Laser-Physik, Universität Hamburg, Hamburg, Germany

The implementation of an adjustable time phase difference into a two dimensional optical square lattice setup with nonseparable lattice potential allows us to excite a large fraction of bosonic atoms from the ground state into higher bands by means of a population swapping technique. The ensemble develops full cross dimensional coherence with a lifetime of up to 150 ms.

Depending on the involved band and the lattice configuration, real-valued striped superfluid order parameters, or complex-valued order parameters which break time reversal symmetry build up. Tuning the anisotropy within the lattice, we are able to map thephase diagram of the transition between this order parameters in the second band (P-band), which exhibits a mixed orbital structure of local S- and P-orbits. The experimental results are compared to a multi-band Bose-Hubbard model calculation, which takes into account next nearest neighbour tunneling and interaction effects.

References

[1] M. Ölschläger *et al.*, *Unconventional Superfluid Order in the F Band of a Bipartite Optical Square Lattice*, Physical Review Letters **106**, No. 1 (2011).

[2] G. Wirth *et al.*, *Evidence for orbital superfluidity in the P-band of a bipartite optical square lattice*, Nature Physics **7**, pp. 147-153 (2011).

[3] M. Ölschläger *et al.*, *Topologically induced avoided band crossing in an optical chequerboard lattice*, ArXiv e-prints (2011).

Dynamics of a kicked Bose-Einstein condensate in disordered potentials

Yafan Duan[1,*], Bonan Jiang[1], Kangkang Liu[1], Jianfang Sun[1], Jun Qian[1], Zhen Xu[1], Tao Hong[2], and Yuzhu Wang[1]

1. Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
2. Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201203, China
**yafan@siom.ac.cn*

We investigate the transport dynamics of a kicked Bose-Einstein condensate (BEC) in a 1D disordered potential generated by laser speckle. It is demonstrated that disorder has remarkable effects on transport behavior of a matter wave packet. The motion of the center of mass is suppressed by disorder and finally the distribution of the BEC is localized. We also analyze the momentum evolution and an unexpected new component appears in the momentum spectrum which is symmetric with the initial momentum. The new symmetric component induces the localization of the center of mass. In the case of the BEC in a quasi-periodic lattice, a similar phenomenon is also demonstrated numerically, however, the novel component of the momentum spectrum emerges asymmetrically.

Using photon statistics to distinguish the atomic phases in a Bose-Hubbard system coupled to a cavity field

Sara Rajaram* and Nandini Trivedi

The Ohio State University, Ohio, USA
**sararajaram@gmail.com*

By numerical simulation, we examine how photon statistics distinguish the Mott-insulating and superfluid phases of lattice bosons. To meet this end, we study a two-band boson system confined to an optical lattice and coupled to a cavity field. Like the Bose-Hubbard model, this Hamiltonian includes local repulsive interactions and nearest neighbor tunneling. In addition, atom-photon coupling induces transitions between the two internal atomic levels. In the presence of a large cavity field, we find different photon number statistics in the Mott-insulating versus superfluid phases, providing a coarse method of distinguishing the atomic phases by photon counting. Furthermore, we examine the dynamics of the photon field after a rapid increase in well depth (a quench to zero atomic hopping). We find a robust relationship, resulting from photon-atom entanglement, between the photon field's quench dynamics and the initial superfluid order parameter. This relationship thereby provides a method of elucidating the degree of superfluidity from photon statistics.

We acknowledge support from ARO W911NF-08-1-0338 (SR), NSF DMR-0907275 (NT), and NSF Graduate Research Fellowship (SR).

Control of Wannier orbitals for generating entanglement of ultracold atoms in an optical lattice

K. Inaba[1,3], Y. Tokunaga[2,3,]*, K. Tamaki[1,3], K. Igeta[1,3], and M. Yamashita[1,3]

1. NTT Basic Research Labs., NTT Corporation, Atsugi, Kanagawa 243-0198, Japan
2. NTT Secure Platform Labs., NTT Corporation, Musashino, Tokyo 180-8585, Japan
3. CREST, JST, Chiyoda-ku, Tokyo 102-0075, Japan
**tokunaga.yuuki@lab.ntt.co.jp*

We propose to exploit Wannier orbitals as controllable quantum states for generating high-fidelity entangled cluster states of ultracold fermionic atoms in an optical lattice [1]. To make this control precise, we treat Wannier orbitals in the ab initio manner. In our method, atoms in the lowest orbital are chosen as qubits, and the extra-Hilbert space that originates from higher orbitals serves as a controllable and accessible environment. By controlling the coupling between the qubits and the environment, we can design interactions among the qubits. Specifically, we create a tunable Ising interaction in adjacent sites to generate entangled cluster states. The fidelity can be enhanced by performing measurements on states of the environment followed by post-selection depending on the resulting outcomes. Moreover, substantial advantages as regards scalability can be obtained by our pair-wise entanglement generation scheme. Precise numerical simulations involving an exact diagonalization confirm that a combination of the above tricks allows us to generate very high-fidelity entanglement with current experimental technologies. The present method is applicable to generating one, two, and three dimensional (1D, 2D, and 3D) cluster states, and thus is suitable for fault-tolerant measurement-based quantum computation.

Reference

[1] K. Inaba, Y. Tokunaga, K. Tamaki, K. Igeta and M. Yamashita, arxiv: 1202.6446.

Ultracold atoms in optical lattices: beyond the Hubbard model

Sebastiano Pilati[1,2,*], Ping Nang Ma[2], Xi Dai[3], and Matthias Troyer[2]

1. The Abdus Salam International Centre for Theoretical Physics, 34014 Trieste, Italy
2. Theoretische Physik, ETH Zurich, 8093 Zurich, Switzerland
3. Institute of Physics, Chinese Academy of Science, Beijing China
**spilati@ictp.it*

We investigate the properties of strongly interacting atomic gases in optical lattices, addressing the regimes of weak and intermediate optical potentials where the conventional description in terms of the single band Hubbard model is not reliable.

In the case of bosonic atoms, we introduce a novel Monte Carlo technique [1] which allows to simulate the superfluid to insulator transition in continuous space.

For fermions, we apply Kohn-Sham Density Functional Theory (DFT), which is the most powerful computational tool routinely used in material science. In this work, we use a new energy-density functional for repulsive Fermi gases with short-range interactions. The first results based on a local spin-density approximation show evidence of a ferromagnetic phase due to repulsive interactions, and of anti-ferromagnetic order at half filling.

Reference

[1] S. Pilati and M. Troyer, *Bosonic Superfluid-Insulator Transition in Continuous Space*, Phys. Rev. Lett. **108**, 155301 (2012).

Quantum computation with ultracold atoms in driven optical lattices

Philipp-Immanuel Schneider* and Alejandro Saenz

AG Moderne Optik, Institut für Physik, Humboldt-Universität zu Berlin, Germany
**philipp.schneider@physik.hu-berlin.de*

In the last years tremendous progress has been made in controlling and observing ultracold atoms in optical lattices. One of the latest developments has been the optical detection of atoms with single site resolution in lattices of increasingly smaller periodicity [1,2]. Along with these detection schemes comes the possibility to control the lattice potential with single-site resolution.

We propose a scheme that makes use of these approved technologies to perform quantum computation in optical lattices. The qubits are encoded in the spacial wavefunction of atoms in the Mott insulator phase such that spin decoherence does not influence the computation. Quantum operations are steered by shaking the lattice while the qubits are addressed by locally changing the lattice potential. Numerical calculations show possible fidelities above 99% with gate times on the order of a few milliseconds [3].

References

[1] W. S. Bakr *et al.* Nature **462**, 74 (2009).
[2] J. F. Sherson *et al.* Nature **467**, 68 (2010).
[3] P.-I. Schneider, A. Saenz preprint arXiv:1103.4950.

Orbital physics in optical lattices: from strong correlations to twisted superfluidity

Dirk-Sören Lühmann*, Ole Jürgensen, Parvis Soltan-Panahi, Julian Struck, Patrick Windpassinger, and Klaus Sengstock

Institut für Laser-Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
**dirk.luehmann@physik.uni-hamburg.de*

We show that multi-orbital and density-induced tunneling have significant impact on the phase diagrams of atoms in optical lattices [1]. In these systems, higher-band processes and off-site interactions are important extensions to the established and well-studied Hubbard model. We introduce dressed operators for the description of multi-orbitally renormalized tunneling, on-site, and so-called bond-charge interactions. Using an extended occupation-dependent Hubbard model, strong changes of the Mott transition for bosonic systems and Bose-Fermi mixtures are predicted. In contrast, phenomena in superfluids are usually well described by the lowest band with a real order parameter. We report on the observation of a quantum phase transition to a novel multi-orbital superfluid phase in hexagonal lattices [2]. In this unconventional superfluid, the local phase angle of the complex order parameter is continuously twisted between neighboring lattice site.

References

[1] D.-S. Lühmann, O. Jürgensen, and K. Sengstock, New J. Phys. 14, 033021 (2012).
[2] P. Soltan-Panahi, D.-S. Lühmann, J. Struck, P. Windpassinger, and K. Sengstock, Nature Physics 8, 71–75 (2012).

Quantum optics of ultracold quantum gases

Igor B. Mekhov

University of Oxford, Department of Physics, Oxford, UK
Igor.Mekhov@physics.ox.ac.uk

Although quantum gases trapped by light represent a broad direction of modern research, the quantum properties of light are usually completely neglected in this field. The study of phenomena, where the quantization of both light and atomic motion is crucial, will lead to the observation of novel effects, beyond traditional physics of many-body systems trapped in prescribed potentials, e.g., optical lattices [1]. First, the light serves as a quantum nondemolition (QND) probe of atomic [1] or molecular [2] states. Second, due to the light-matter entanglement, the measurement-based preparation of many-body states is possible (number squeezed, Schrödinger cat states, etc.) [3]. Light scattering constitutes quantum measurement with controllable measurement back-action, allowing the dissipation tailoring. Third, in cavity QED with quantum gases, the self-consistent solution for light and atoms is required, enriching phases of atoms trapped in quantum potentials and strengthening quantum simulations [1].

References

[1] I. B. Mekhov and H. Ritsch, "REVIEW. Quantum Optics with Ultracold Quantum Gases: towards the full quantum regime of the light-matter interaction," arXiv:1203.0552.
[2] B. Wunsch, N. T. Zinner, I. B. Mekhov, S.-J. Huang, D.-W. Wang, and E. Demler, "Few-body bound states in dipolar gases and their detection," Phys. Rev. Lett. **107**, 073201 (2011).
[3] I. B. Mekhov and H. Ritsch, "QND measurements and state preparation in quantum gases by light detection", Phys. Rev. Lett. **102**, 020403 (2009).

Quantum gas microscopy: magnetism and algorithmic cooling

Philipp Preiss, Ruichao Ma, M. Eric Tai, Jonathan Simon, and Markus Greiner*

Department of Physics, Harvard University, Cambridge, Massachusetts, 02138, USA
**greiner@physics.harvard.edu*

Ultracold atoms in optical lattices are an ideal system for the quantum simulation of condensed matter systems, offering high tunability of parameters in dissipation-free systems. With quantum gas microscopy, we are now able to initialize, manipulate and probe strongly-interacting many-body systems on a single-particle level.

We utilize this high degree of control for the first realization of quantum magnetism in an optical lattice and report on microscopic studies of a quantum phase transition in antiferromagnetic Ising spin chains. We also present a new in-lattice cooling technique suitable for cooling to the pico-Kelvin regime: Using an orbital-dependent interaction, we demonstrate a number-filtering technique that enables the algorithmic removal of entropy from a thermal cloud until it Bose condenses.

This work opens new opportunities for the creation and study of strongly-correlated systems in optical lattices.

Quench dynamics of the Bose Josephson junction with impurities

D. H. J. O'Dell

Department of Physics & Astronomy, McMaster University, 1280 Main St. W., Hamilton, Ontario L8S 4M1, Canada
dodell@mcmaster.ca

There is currently considerable interest in whether/how isolated quantum systems thermalize following a quench. In this theoretical work we consider the dynamics of the Bose Josephson junction (BJJ) for which exact results can be obtained. In particular, we show that following a sudden lowering of the tunneling barrier from the Fock to the Josephson regime the quantum system quickly relaxes towards the classical ergodic distribution. However, fluctuations about this ergodic average remain and are characteristic of rainbow and cusp singularities that proliferate in the many-body wave function following the quench [1]. Crucially, the BJJ is an integrable system. However, when impurity atoms are added it becomes classically chaotic and we investigate how this affects the long-time dynamics and ergodicity following a quench.

Reference

[1] D. H. J. O'Dell, "Quantum rainbows and ergodicity in many-body dynamics", arXiv:1202.1341.

All optical formation of Ytterbium two-dimensional quasi-condensate near surface of solid immersion lens

Martin Miranda[1], Akimasa Nakamoto[1], Yuki Okuyama[1], Atsushi Noguchi[1,†], Masahito Ueda[2], and Mikio Kozuma[1]

1. Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo, Japan
2. Tokyo University, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
**miranda.m.aa@m.titech.ac.jp*
† Present affiliation: Osaka University

Neutral atoms trapped in a two dimensional optical lattice have demonstrated to be a novel candidate for studying interacting many-body quantum systems and creating quantum simulators. In recent years, a high resolution microscope system consisting of a solid immersion lens (SIL) and a high num-erical aperture objective lens was utilized to detect single rubidium atoms in a Hubbard-regime [1]. ^{171}Yb is an promising candidate for a quantum bit, because it possesses 1/2 nuclear spin and no electronic spin, which ensures long coherence times compared with alkali atoms. We present an all optical method to load ^{174}Yb atoms into a single layer of optical trap near the SIL. 5×10^5 atoms are cooled down to 2 μK and then transported, using two crossed ODT, to a distance of 25 μm under the SIL. After that, the optical accordion technique is used to create a condensate and compress the atoms to a distance of 1.8 μm. The characteristic time-of-flight shape of the 2D quasi-condensate was observed.

Reference

[1] W. S. Bakr, J. I. Gillen, A. Peng, S. Fölling and M. Greiner, *A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice*, Nature **462**, pp. 74-78 (2009).

Lattice modulation spectroscopy with spin-1/2 fermions in spin-incoherent regime

Akiyuki Tokuno[1,*], Eugene Demler[2], and Thierry Giamarchi[1]

1. DPMC-MaNEP, University of Geneva, 24 Quai Ernest-Ansermet CH-1211 Geneva, Switzerland
2. Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
**Akiyuki.Tokuno@unige.ch*

Recent development of the spectroscopy by modulation of optical lattice potentials allows us to access excitation structure of strongly correlated systems, [1] in which the created doubly occupied sites (doublons) number is measured. In the theoretical viewpoint, the doublon production rate (DPR) allows us to access to a correlation function of the kinetic energy.

We discuss doublon excitations in spin-incoherent Mott insulators which are relevant to current experiments of fermionic atoms in optical lattice potentials. [2] To describe charge excitations in such a system, slave particle representation and diagrammatic approach based on non-crossing approximation under the assumption of a spin-incoherent state are used, and the single particle spectrum function is estimated. Applying this formalism to the calculation of the DPR by lattice modulation, we implement a fit to the experiment [1], and as a result the quantitatively good agreement is obtained.

References

[1] D. Greif, L. Tarruell, T. Uehlinger, R. Jördens, and T. Esslinger, *Probing Nearest-Neighbor Correlations of Ultracold Fermions in an Optical Lattice*, Phys. Rev. Lett. **106**, 145302 (2011).
[2] A. Tokuno, E. Demler, and T. Giamarchi, *Doublon production rate in modulated optical lattices*, Phys. Rev. A **85**, 053601 (2012).

Towards site-resolved imaging and control of ultracold fermions in optical lattices

Florian Huber, Maxwell F. Parsons, Widagdo Setiawan, Katherine Wooley-Brown, Sebastian Blatt, and Markus Greiner

Department of Physics, Harvard University, Cambridge, Massachusetts, 02138, USA

Recent successes in site-resolved imaging and control of bosonic atoms trapped in optical lattices have enabled many new possibilities to emulate simple condensed matter systems. Many of the open questions in condensed matter, however, stem from the fermionic nature of electrons. Extending the high degree of control available with ultracold quantum gases in optical lattices to fermionic atoms will allow us to address these questions. The light mass of fermionic ^{6}Li leads to system dynamics on fast timescales, making it an ideal candidate for such studies. We report progress toward a ^{6}Li quantum gas microscope and present improved imaging, cooling, and trapping techniques compatible with the light mass of ^{6}Li.

Probing atomic dynamics in a moving optical lattice with near-resonant fluorescence spectroscopy

Jung-Ryul Kim, Sungsam Kang, Myounggyu Hwang, Soonki Hong, and Kyungwon An*

Quantum-Field Laser Laboratory, Department of Physics and Astronomy, Seoul National University, Seoul, Korea
**contact. kwan@phya.snu.ac.kr*

We have recently observed nanometer-scale atomic localization and matter-wave tunneling in a stationary optical lattice in a phase-stabilized magneto-optical trap(MOT) of ^{85}Rb atoms[1]. We have extended the study to the case where the optical lattice is moving, which is realized by introducing a frequency difference between counter-propagating trap lasers. When the speed v of the optical lattice is much smaller than the mean oscillation velocity v_{osc} associated with the lattice potential, most of the atoms were transported by the lattice while localized at the lattice potential minima and thus exhibiting a Rayleigh peak and Raman sidebands in the spectrum. However, when v is increased beyond v_{osc}, Doppler-broadened spectral feature appeared and grew, indicating atoms were no longer localized. We measured the evolution of the spectrum with the increased lattice speed systematically. We will report the results so far, and analyze data with a simple model incorporating transitions among the vibrational states of the lattice potential.

Reference

[1] W. Kim *et al.,* "Tunneling-induced spectral broadening of a single atom in a three-dimensional optical lattice", Nano Lett. **11**, 729 (2011).

Lifetimes of three particles in an isotropic harmonic trap

Edmund R. Meyer* and B. D. Esry

Department of Physics, Kansas State University
**meyere@phys.ksu.edu*

We present an analytic calculation of the energy levels and decay rates of particles confined by an isotropic harmonic trap. Using a single adiabatic hyperspherical channel, we derive a transcendental equation whose solutions give the energy levels and decay rates of the trapped states. To gain a more physical interpretation of the results, we examine two regimes: the oscillator length much greater than, and much less than, the two-body *S*-wave scattering length. For the case of a large oscillator length, we find explicit analytic expressions for the decay rate of the trapped states. We find that the decay rate for bosons scales as $|a|^4$ (in agreement with prior work on free-space recombination), with higher-order corrections due to the trap. Moreover, the decay rate shows resonant enhancements due to Efimov physics just as free space rates do. In addition, we show that for a small oscillator length, the decay rate is proportional to the trapping frequency and exhibits log-periodic behavior.

Supported by the National Science Foundation.

Quantum information Th-110

Temporally multiplexed storage of images in a gradient echo memory

Quentin Glorieux[1,*], Jeremy B. Clark[1], Zhifan Zhou[1], Alberto M. Marino[1], and Paul D. Lett[3]

1. Quantum Measurement Division, National Institute of Standards and Technology and Joint Quantum Institute, NIST, and the University of Maryland, Gaithersburg, MD 20899, USA
**quentin.glorieux@nist.gov*

In this paper we have demonstrated that the optical gradient echo memory is suitable for the coherent storage of images. We experimentally study the effect of atomic diffusion on the quality of an image stored in the long-lived ground state coherence of a warm atomic ensemble. We show that the maximum spatial frequency that can be stored is predetermined by the storage time and the diffusion coefficient of the medium. Additionally, we study the ability of this memory to store multiple images at the same time, allowing temporal and spatial multiplexed storage in an atomic vapor [1]. Finally, we would like to emphasize that this setup is perfectly adapted to be combined with recent experiments on the generation of squeezed states and entangled images [2] with four-wave mixing in a hot rubidium vapor.

References

[1] Q. Glorieux, J. B. Clark, A. M. Marino, Z. Zhou, and P. D. Lett, *Temporally multiplexed storage of images in a Gradient Echo Memory*, Optics Express **20**, pp. 12350-12358 (2012).
[2] V. Boyer, A. M. Marino, R. C. Pooser, and P. D. Lett, *Entangled Images from Four-Wave Mixing*, Science **321**, 544 (2008).

Quantum frequency conversion of nonclassical light – from InAs quantum dots into telecomm window

Jason Pelc[1], Leo Yu[1], Kristiaan De Greve[1], Chandra Natarajan[1,4], Peter McMahon[1], Christian Schneider[3], Na Young Kim[1], Eisuke Abe[1], S. N. Dorenbos[5], E. Bermúdez Ureña[5], T. Zijlstra[5], T. M. Klapwijk[5], V. Zwiller[5], Qiang Zhang[2], Robert Hadfield[4], Sven Hofling[3], Alfred Forchel[3], Martin Fejer[1], and Yoshihisa Yamamoto[1]

1. Edward L. Ginzton Laboratory, Stanford University
2. University of Science and Technology of China
3. Physikalisches Institut, Universitat Wurzburg
4. Heriot-Watt University
5. Kavli Institute for Nanoscience, Delft University of Technology

InAs Quantum Dots (QDs) are ideal building block of quantum repeaters for its quantum emitting and spin-coherence properties. The quantum information from a spin qubit can be transferred to the polarization of a photon. Using those features long-haul entanglement establishment among spin qubits can be potentially achieved. We have made progress on this spin-photon interface. We convert ~910 nm emitted photons from the QDs to ~1560 nm by frequency downconversion using Periodically Poled Lithium Niobate(PPLN) waveguides. A total system conversion efficiency about 70% is demonstrated whereas the noise photon is below one count per second. From this we demonstrate ultrafast detection (< 10ps) of single photons, and preservation of second order correlation function during conversion process.

An adiabatic approach to quantum computing using Rydberg-*dressed* neutral atoms

L. P. Parazzoli[1,*], A. Hankin[1,2], J. Chau[1], Y. Jau, C. Johnson[1], P. Schwindt[1], B. Keating[2], I. Deutsch[2], A. Landahl[1,2], and G. Biedermann[1,2]

1. Sandia National Laboratories, Albuquerque NM, USA
2. Center for Quantum Information and Control (CQuIC), University of New Mexico, Albuquerque NM, USA
**lpparaz@sandia.gov*

We are implementing an adiabatic quantum computation (AQC) algorithm using neutral atoms trapped in optical tweezers with interactions mediated via the Rydberg blockade mechanism [1]. Adiabatic evolution offers potential to solve computationally difficult problems by mapping the problem of interest onto the Hamiltonian such that the ground state encodes the solution. To find the solution, one begins by initializing in the ground state of a 'simple' Hamiltonian and then evolving adiabaticallyto the 'problem' Hamiltonian. Neutral atoms offer advantages because of their demonstrated robust quantum coherence (e.g. atomic clocks), long lived hyperfine states (the qubit basis), and also because they are highly isolated from the external environment. We control the adiabatic evolution of the system by imposing various light shifts on the hyperfine levels. The interaction between the atoms is generated by creating a Rydberg-dressed state [2] that, via Rydberg blockade, creates the necessary conditional shift.

References

[1] D. Jaksch, *et al.*, Phys. Rev. Lett. **87**, 037901 (2001).
[2] Rolston, *et al.*, Phys. Rev. A, **82**, 033412 (2010).

Non-Markovianity, Loschmidt echo and criticality: a unified picture

P. Haikka[1,*], J. Goold[2,3], S. McEndoo[1,4], F. Plastina[5,6], and S. Maniscalco[1,4]

1. Turku Center for Quantum Physics, Department of Physics and Astronomy, University of Turku, Turku, Finland
2. Clarendon Laboratory, University of Oxford, Oxford, UK
3. Physics Department, University College Cork, Cork, Ireland
4. SUPA, EPS/Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK
5. Dipartimento di Fisica, Università della Calabria, 87036 Arcavacata di Rende (CS), Italy
6. INFN–Gruppo Collegato di Cosenza, Italy
**pmehai@utu.fi*

A simple relationship between recently proposed measures of non-Markovianity and the Loschmidt echo is established, holding for a two-level system (qubit) undergoing pure dephasing due to a coupling with a many-body environment. We show that the Loschmidt echo is intimately related to the information flowing out from and occasionally back into the system. This, in turn, determines the non-Markovianity of the reduced dynamics. In particular, we consider a central qubit coupled to a quantum Ising ring in the transverse field. In this context, the information flux between system and environment is strongly affected by the environmental criticality; for a reasonable time truncation the qubit dynamics is shown to be Markovian exactly and only at the critical point. Therefore non-Markovianity is an indicator of criticality in the model considered here.

Reference

[1] P. Haikka, J. Goold, S. McEndoo, F. Plastina, and S. Maniscalco, arXiv:1202.2997 (2012).

Narrowband source of correlated photon pairs via four-wave mixing in atomic vapour

Bharath Srivathsan[1],Gurpreet Kaur Gulati[1], Chng Mei Yuen Brenda[1],
Gleb Maslennikov[1], Dzmitry Matsukevich[1,2], and Christian Kurtsiefer[1,2]

1. Centre for Quantum Technologies, National University of Singapore, Singapore 117543
2. Department of Physics, National University of Singapore, Singapore 117542

Many quantum communication protocols require entangled states of distant qubits which can be implemented using photons. To efficently transfer entanglement from photons to stationary qubits such as atoms, one requires entangled photons with a frequency bandwidth matching the absorption profile of the atoms. In our setup, a cold Rb^{87} atomic ensemble is pumped by two laser beams (780nm and 776nm) resonant with the $5S_{1/2} \rightarrow 5P_{3/2} \rightarrow 5D_{3/2}$ transition. This generates time-correlated photon pairs (776nm and 795nm) by nondegenerate four-wave mixing via the decay path $5D_{3/2} \rightarrow 5P_{1/2} \rightarrow 5S_{1/2}$. Coupling the photon pairs into single mode fibres and using silicon APDs, we observe a $g^{(2)}$ of about 4750 and pairs to singles ratio of 14.2% (400 photon pairs per second). By filtering out uncorrelated 795nm photons, we obtain a pairs to 795nm singles ratio of 18.4%. The optical bandwidth of the pairs was measured by a cavity (linewidth 2.8MHz) to be 21.4MHz for a MOT optical density of 26.

Reference

[1] Willis, R. T. *et al. Four-wave mixing in the diamond configuration in an atomic vapor*, Phys. Rev. A **79**, pp. 033814 (2009).

All-optical phase modulation based on a double-Lambda atomic system

Yen-Chun Chen, Hao-Chung Chen, Hsiang-Yu Lo, Bing-Ru Tsai, and Yong-Fan Chen*

Department of Physics, National Cheng Kung University, Tainan, Taiwan
**yfchen@mail.ncku.edu.tw*

The technique of controlling the optical phase of a light pulse by another is called cross-phase modulation (XPM), and can be applied to implement controlled-phase gates and quantum entangled states. Although there are several proposed methods to enhance nonlinear optical effects at the single photon level, the interaction between two light fields is normally too small for quantum information applications. Electromagnetically induced transparency (EIT) is one of the most promising technologies for achieving strong optical nonlinearities and the coherent manipulation of light. Here we experimentally demonstrate a novel scheme of XPM based on a phase-dependent double-Lambda atomic system. This work opens a new route to generate strong nonlinear interactions between photons, and may have potential for applications in quantum information technologies.

EIT-based storage in warm and cold ensembles of cesium atoms

A. Sheremet[1,2], L. Giner[1], L. Veissier[1], A. Nicolas[1], D. Maxein[1], B. Sparkes[3], O. S. Mishina[4], M. Scherman[1,5], D. V. Kupriyanov[2], P. K. Lam[3], E. Giacobino[1], and J. Laurat[1]

1. Laboratoire Kastler Brossel, Université P. et M. Curie, Ecole Normale Supérieure, Paris, France
2. Department of Theoretical Physics, State Polytechnic University, Saint-Petersburg, Russia
3. Center for Quantum Computation and Communication Technology, Australian National University, Canberra, Australia
4. Universität des Saarlandes, Theoretische Physik, Saarbrücken, Germany
5. ONERA, The French Aerospace Lab, Chemin de la Huniere, Palaiseau, France

We investigate and compare atomic cesium gases at room temperature and in a cold atomic cloud for their usability in quantum memory protocols based on the effect of electromagnetically induced transparency (EIT). In order to improve the storage and retrieval characteristics we have performed a detailed theoretical and experimental study of EIT. Taking into account the full hyperfine structure and the Zeeman splitting in the considered atomic transition, we show that they modify the dynamics of EIT, but also permit for its customization.

The model is applied and compared to our experiments. In the warm vapor, the targeted depletion of perturbing velocity classes can enhance the EIT effect significantly. In the cold ensemble, consisting of atoms collected into a magneto-optical trap, we demonstrated EIT based storage of orbital angular momentum in the single-photon regime. We also investigated an experimental witness recently proposed by P. M. Anisimov *et al.* that allows for disambiguation between EIT and Autler-Townes splitting. Again the full structure plays here an important role.

Quantum processing of polarization qubits in a Λ-type three-level medium

D. Viscor[1], A. Ferraro[1], Yu. Loiko[1,2], J. Mompart[1], and V. Ahufinger[1,*]

1. Departament de Física, Universitat Autònoma de Barcelona, Bellaterra, Spain
2. Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
**veronica.ahufinger@uab.cat*

We address the propagation of a single photon pulse with two polarization components, i.e., a polarization qubit, in an inhomogeneously broadened “phaseonium” Λ-type three-level medium. We combine some of the characteristic propagation effects for the phaseonium media with the controlled reversible inhomogeneous broadening (CRIB) technique to propose novel quantum information processing applications [1]. Since part of the incident pulse, i.e., the antisymmetric normal mode, uniquely determined by the preparation of the atoms in the phaseonium state, propagates without distortion while the symmetric normal mode can be efficiently and completely absorbed, the system acts as a quantum filter. Moreover, the absorbed part of the incident field can be retrieved in the backward direction using the CRIB method. In this case, the system can be used as a quantum sieve or, considering both orthogonal modes, a tunable polarization qubit splitter. Moreover, we show that, by imposing a spatial variation of the atomic coherence phase, both field components can be completely absorbed and an efficient quantum memory for the incident polarization qubit can be also implemented.

Reference

[1] D. Viscor, A. Ferraro, Yu. Loiko, J. Mompart and V. Ahufinger, *Quantum state storage and processing for polarization qubits in an inhomogeneously broadened Λ-type three-level medium*, Phys. Rev. A **84**, 042314(1)-042314(9) (2011).

Quantum information Th-118

Interaction of ultracold atoms and superconducting micro-structures

S. Bernon*, H. Hattermann, P. Weiss, F. Jessen, D. Cano, D. Bothner, M. Knufinke, M. Kemmler, D. Koelle, R. Kleiner, and J. Fortágh*

Physikalisches Institut, Eberhard-Karls-Universität, Tübingen, Germany
**simon.bernon@uni-tuebingen.de and fortagh@uni-tuebingen.de*

Hybrid quantum systems, which combine ultra-cold atoms with superconducting solid-state devices, have been proposed in the areas of precision sensing and quantum information processing. Such systems, exploit the rapidity of quantum logical operations performed by solid-state devices together with the long coherence time of atomic quantum superposition states.

We report on the interaction of ultracold atoms and superconducting Niobium microstructures at 4.2 K. The atomic cloud is prepared and cooled to degeneracy on a superconducting atomchip. The interaction of the atoms with the superconducting trapping structure was observed both in a distortion of the trap due to the Meissner effect and in a suppression of the Johnson-Nyquist noise that manifests itseld in long trap lifetimes. We present recent Ramsey interferometry measurements of the coherence lifetime of atomic spin state superpositions trapped on a superconducting atomchip.

As a further step towards the interaction of these two quantum systems, we recently implemented a hybrid trap incorporating the magnetic field generated by a superconducting ring holding a few trapped flux quantas. In this hybrid trap, the flux quantization in the ring was observed and characterized.

RF and microwave based quantum information science with cold ions

M. Johanning[1,*], I. Baumgart[1], T. F. Gloger[1], A. Khromova[1], C. Piltz[1], M. B. Plenio[2], A. Retzker[2], B. Scharfenberger[1], N. Timoney[1], A. Varon[1], and Ch. Wunderlich[1]

1. Lehrstuhl Quantenoptik, Science and Technology, University of Siegen, Siegen, Germany
2. Institut für Theoretische Physik, University of Ulm, Ulm, Germany
**johanning@physik.uni-siegen.de*

Trapped ions exposed to a magnetic gradient and manipulated with long-wavelength radiation exhibit an effective spin-spin interaction which is used to carry out CNOT gates with thermally excited ions using microwave radiation [1]. We characterize experimentally the spin-spin-coupling in strings of two and three ions and prove the dependence of this coupling on the trap frequency which can be used to create tailored coupling patterns relevant for quantum simulations.

Decoherence due to fluctuating magnetic fields can be strongly suppressed using microwave-dressed states [2] and coherence times up to about 1 s are achieved. At the same time, using dressed states eliminates carrier transitions by interference and retains the magnetic gradient-induced coupling. Thus, fast quantum gates even with a small effective Lamb-Dicke-parameter are possible. This approach is generic and applicable also to laser-based gates as well as other types of physical qubits.

References

[1] A. Khromova, Ch. Piltz, B. Scharfenberger, T. F. Gloger, M. Johanning, A. F. Varón, and Ch. Wunderlich, arXiv:1112.5302v1 [quant-ph] (2011).
[2] N. Timoney, I. Baumgart, M. Johanning, A. F. Varón, M. B. Plenio, A. Retzker, and Ch. Wunderlich, Nature **476**, 185-188 (2011).

Th-120 Quantum information

Room temperature quantum bit memory exceeding one second

G. Kucsko[1], P. C. Maurer[1], C. Latta[1], L. Jiang[2], N. Y. Yao[1], S. D. Bennett[1], F. Pastawski[3], D. Hunger[4], N. Chisholm[4], M. Markham[5], D. J. Twitchen[5], J. I. Cirac[3], and M. D. Lukin[1,*]

1. Department of Physics, Harvard University, Cambridge, MA 02138, USA
2. Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA
3. Max-Planck-Institut für Quantenoptik, Garching, D-85748, Germany
4. School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
5. Element Six Ltd, Ascot SL5 8BP, UK
**contact.lukin@physics.harvard.edu*

Realization of stable quantum bits (qubits) that can be prepared and measured with high fidelity and that are capable of storing quantum information for long times exceeding seconds is an outstanding challenge in quantum science and engineering. Here we report on the realization of such a stable quantum bit using an individual ^{13}C nuclear spin within an isotopically purified diamond crystal at room temperature. Using an electronic spin associated with a nearby Nitrogen Vacancy color center, we demonstrate high fidelity initialization and readout of a single ^{13}C qubit. Quantum memory lifetime exceeding one second is obtained by using dissipative optical decoupling from the electronic degree of freedom and applying a sequence of radio-frequency pulses to suppress effects from the dipole-dipole interactions of the ^{13}C spin-bath. Techniques to further extend the quantum memory lifetime as well as the potential applications are also discussed.

Ultra-narrow single photons for atomic gradient echo memory storage

Till J. Weinhold*, Juan C. Loredo, Michael S. Stefszky, and Andrew G. White

Centre for Engineered Quantum Systems and Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, The University of Queensland, QLD 4072, Australia
**t.weinhold@uq.edu.au*

Quantum communication requires transmission of quantum information over large distances. Photons are predestined for such a task due to their inherent high mobility and low decoherence. Quantum information processing will require the ability to locally store and access quantum data [1]. For this photonic qubits are unsuitable. Their information needs to be transferred to a quantum memory. Gradient echo memories (GEM) have demonstrated storage and recall efficiencies larger than 80%, while theoretical efficiencies as high as 98% are possible [2]. The challenge to utilising a memory based on GEM as with any atomic quantum memory is the vast difference between the spectral properties of the memory and the single photons It has been shown that the emission spectra of parametric down-conversion (PDC) can be significantly reduced by using a cavity [3]. Here we report our work towards the generation of single photons from cavity enhanced PDC suitable for storage in a GEM memory.

References
[1] W. Tittle, *et al., Photon-echo quantum memory in solid state systems*, Laser & Photon. Rev. **4**, 244-267 (2010).
[2] M. Hosseini, *et al.*, *High efficiency coherent optical memory with warm rubidium vapour*, Nat. Comm. **2**, 174 (2011).
[3] Z. Y. Ou, Y. J. Lu, *Cavity enhanced spontaneous parametric down-conversion for the prolongation of correlation time between conjugate photons* Phys. Rev. Lett. **83**, 223601 (2006).

Quantum information Th-122

Trapping cold neutral atoms with evanescent optical fields for a hybrid quantum system[1]

J. Lee[1,*], J. A. Grover[1], J. E. Hoffman[1], S. Ravets[1,3], Z. Kim[1], K. D. Voigt[1], S. Mittal[2], M. Dagenais[2], M. Hafezi[1], J. M. Taylor[1], J. R. Anderson[1], C. J. Lobb[1], L. A. Orozco[1], S. L. Rolston[1], and F. C. Wellstood[1]

1. Joint Quantum Institute, Dept. of Physics, UMD and NIST, College Park, MD 20742, USA
2. Dept. of ECE, University of Maryland, College Park, MD 20742, USA
3. Laboratoire Charles Fabry, Institut d'Optique, CNRS Univ Paris-Sud, Campus Polytechnique, RD 128, 91127 Palaiseau cedex, France
**neoscien@umd.edu*

We explore uses of atoms trapped in the evanescent optical field near a nanofiber for atomtronics and quantum information. Rb atoms trapped in the evanescent field can be coupled to the magnetic field of a superconducting (SC) resonator operating close to the Rb ground state hyperfine frequency (6.8 GHz). This is a first step towards coupling atoms to a SC qubit. We are combining a grating MOT (GMOT) with an evanescent field trap, so that optically-trapped atoms loaded from a GMOT can be transported and coupled to a SC resonator in a dilution refrigerator. We will present results from nanofiber fabrication, a GMOT setup, and nano-photonic structures, and we discuss experimental proposals for hybrid quantum systems.

This work is supported by ARO MURI award W911NF0910406, Fulbright, and the NSF Physics Frontier Center at the JQI.

Expanding the experimental frontiers of heralded operations for quantum communications

Jean Etesse[1,†], Rémi Blandino[1], Philippe Grangier[1], and Rosa Tualle-Brouri[1,2]

1. Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique, RD128 91127 Palaiseau Cedex, France
2. Institut Universitaire de France, 103 boulevard St. Michel, 75005, Paris, France
† jean.etesse@institutoptique.fr

Recent progress have been done in the experimental preparation of quantum states designed for continuous variable quantum communication. States prepared with a combination of photon counting and homodyne measurement showed high interest in this domain. Cat states have for instance been characterized a few years ago with this method , revealing a specific quantum feature : a Wigner function with negative values [1]. The main issue of these states is that their quality is not good enough to be used for quantum communication. In other words, the Wigner function is not negative enough.

We propose here to show some ways to improve this quality. One of them concerns the spatial ratio of the beam waists in the parametric amplifier that gives birth to our states.

Reference
[1] A. Ourjoumstev, R. Tualle-Brouri, J. Laurat, P. Grangier, *Generating optical Schrödinger kittens for quantum information processing*, Science **312**, pp. 83-86 (2006).

Effective Hamiltonians and entangled coherent states in a bimodal cavity

F. O. Prado, F. S. Luiz, J. M. Villas-Bôas, A. M. Alcalde, E. I. Duzzioni, and L. Sanz*

Instituto de Física, Universidade Federal de Uberlândia, 38400-902, Uberlândia-MG, Brazil
**lsanz@infis.ufu.br*

In this work, we demonstrate a procedure for engineering effective interactions between two modes in a bimodal cavity. We consider one or more two-level atoms, excited by a classical field, interacting with both modes. The two effective Hamiltonians have a similar form of a beam-splitter and quadratic beam-splitter interactions, respectively. We shown that the nonlinear Hamiltonian can be used to prepare an entangled coherent state, also known as multidimensional entangled coherent state, which has been pointed out as an important entanglement resource. We also show that the nonlinear interaction parameter can be enhanced considering N independent atoms trapped inside a high-finesse optical cavity.

This work was supported by the Brazilian National Institute of Science and Technology for Quantum Information (INCT-IQ) and for Semiconductor Nanodevices (INCT-DISSE), CAPES, FAPEMIG and CNPq.

Cavity cooling below the recoil limit

Hans Kessler, Jens Klinder, Matthias Wolke, Julian Klinner, and Andreas Hemmerich*

Institute of Laser Physics, University of Hamburg, Hamburg, Germany
**hemmerich@physnet.uni-hamburg.de*

Conventional laser cooling relies on repeated electronic excitations by near-resonant light, which constrains its area of application to a selected number of atomic species prepared at moderate particle densities. Optical cavities with a Purcell factor exceeding unity allow to implement laser cooling schemes using off-resonant light-scattering, which avoid the limitations imposed by spontaneous emission. Here, we report on an atom-cavity system, combining a Purcell factor around 40 with a cavity bandwidth(9 kHz) below the recoil frequency associated with the kinetic energy transfer in a single photon scattering event (14 kHz). This lets us access a yet unexplored fundamental quantum mechanical regime of atom-cavity interactions, in which the atomic motion can be manipulated by targeted dissipation with sub-recoil resolution. We demonstrate cavity-induced heating of a of ^{87}Rb Bose-Einstein condensate and subsequent cooling at particle densities and temperatures incompatible with conventional laser cooling.

Modification of in- and off-plane spontaneous emission of active medium in two-dimensional photonic crystals

Ya-Chih Tsai[1,*], Chih-Sheng Chang[1], and Rong Fuh. Louh[2]

1. Department of Photonics, Feng Chia University, Taichung, Taiwan
2. Department of Materials Science and Engineering, Feng Chia University, Taichung, Taiwan
**yctsai@fcu.edu.tw*

According to the Purcell's effect, the introduction of photonic crystal structures may change the electromagnetic mode distribution and affect the spontaneous emission of active medium [1]. We employed the plane-wave expansion method together with a dipole model to study this phenomenon by calculating the local density of states (LDOS) of photons [2]. Although the photonic crystals are assumed two-dimensional for the ease of fabrication, the propagation of photons are allowed to be three-dimensional. We calculated the in- and off-plane LDOS for active medium embedded at various positions of the unit cell. Both LDOS are found to be position-sensitive and they may differ significantly. This indicates that one may use this approach to evaluate the efficiency and even to design the emission pattern of a photonic system such as a light-emitting diode [3].

References
[1] Masayuki Fujita *et al.*, "Simultaneous Inhibition and Redistribution of Spontaneous Light Emission in Photonic Crystals", Science 308, 1296 (2005).
[2] K. Busch *et al.*, "*Photonic Crystals*", p. 24-25 (Wiley-VCH, 2004).
[3] Y.-W. Cheng *et al.*, "GaN-based LEDs surrounded with a two-dimensional nanohole photonic crystal structure for effective laterally guided mode coupling", Opt. Lett. 36, 9 (2011).

Quantum homodyning of photonic qubits, qutrits and ququads emitted on demand from an atomic source

A. Holleczek, P. B. R. Nisbet-Jones, J. Dilley, O. Barter, and A. Kuhn*

University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK
**axel.kuhn@physics.ox.ac.uk*

With single quantum systems controlled to encode elementary quantum bits (qubits) of information, a fundamental enhancement of computing and information security is now in reach. Particular attention is paid to QIP in linear-optics quantum circuits (LOQC) [1], which are in principle scalable to larger networks if it were not for the spontaneous nature of parametric down conversion (PDC) photon sources.

Here, we demonstrate that single photons deterministically emitted from a single atom into an optical cavity [2] can be equally used for LOQC, thus levying these restrictions. With a coherence time of ≈ 500 ns, also a subdividision of photons into several time bins of arbitrary amplitudes and phases is possible. In particular, in place of storing a simple qubit in one photon (being present or absent), the subdivision into d time bins is now used to encode arbitrary qudits in one photon [3]. We verify the fidelity of the encoding with a series of time-resolved quantum-homodyne measurements.

References
[1] E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001).
[2] P. B. R. Nisbet-Jones, J. Dilley, D. Ljunggren, and A. Kuhn, New J. Phys. **13**, 103036 (2011).
[3] P. B. R. Nisbet-Jones, J. Dilley, A. Holleczek, O. Barter, and A. Kuhn, arXiv:1203.5614 [quant-ph] (2012).

Rydberg atoms and surface polaritons

Sofia Ribeiro* and Stefan Scheel

Quantum Optics and Laser Science, Blackett Laboratory, Imperial College London
**s.de-carvalho-ribeiro@imperial.ac.uk*

The presence of macroscopic bodies can drastically change the properties of the electromagnetic field. A manifestation of the body-induced change of the ground-state fluctuations of the field is the Casimir-Polder force experienced by an atom near a dielectric body [1]. To understand experimental results it is necessary to consider realistic scenarios. We strive to understand the interplay between surface plasmon resonances,ambient temperature, surface geometry and the modifications of the atomic structure. The experiment of Kübler *et al.* [2] indicated that a description of the atom-surface interactions should include the possible coupling between the atomic transitions and thermally excited surface polaritons (SP). We derive a quantum description introducing a nonlinear effective Hamiltonian in which the atom can couple resonantly to the SP modes of the dielectric material which leads to second-order energy exchanges with the atomic transition energy matching the difference in SP energies.

References
[1] S. Scheel and S. Y. Buhmann, *Macroscopic quantum electrodynamics concepts and applications*, Acta Phys. Slov. **58**, 675810, 2008.
[2] H. Kübler, J. P. Shaffer, T. Baluktsian, R. Löw and T. Pfau,*Coherent excitation of Rydberg atoms in micrometre-sized atomic vapour cell*, Nature Photonics, **4**, 112-116, 2010.

Atomic excitation and quantum memory with propagating pulses

Yimin Wang[1,*], Jiří Minář[1], Gabriel Hétet[2], and Valerio Scarani[1,3]

1. Centre for Quantum Technologies, National University of Singapore, Singapore
2. Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria
3. Department of Physics, National University of Singapore, Singapore
**vivhappyrom@gmail.com*

Strong interaction between atoms and propagating light is important in quantum information processing, and remains as a current experimental challenge. First, we consider the interaction of a single two-level atom with quantized light pulses propagating in free space. We show the dependence of the atomic excitation on (i) the state of the pulse and (ii) the overlap between the pulse waveform and the atomic dipole pattern [1]. A detailed study of atomic excitation with both n-photon Fock stateand coherent state pulses in various temporal shapes is presented. Second, we propose a quantum memory setup based on a single atom in a half cavity with a moving mirror [2]. We show that various shapes of incident photon can be efficiently stored and readout by shaping the time-dependent atom-pulse coupling. We present how the storage efficiency depends on pulse bandwidth. We discuss the experimental implementations with a single atom/ion in a half cavity and a superconducting qubit in circuit QED.

References

[1] Y. Wang *et al.*, *Efficient excitation of a two-level atom by a single photon in a propagating mode*, Phys. Rev. A **83**, 063842 (2011).
[2] Y. Wang *et al.*, *Quantum memory with a single two-level atom in a half cavity*, Phys. Rev. A **85**, 013823 (2012).

Damping of polariton modes of Bose-Einstein condensates in an optical cavity

G. Szirmai, G. Konya, D. Nagy, and P. Domokos

Wigner Research Centre of the Hungarian Academy of Sciences, Budapest, Hungary
szirmai.gergely@wigner.mta.hu

An important example of strongly correlated systems is a Bose-Einstein condensate in a high-finesse optical resonator. Such a system realizes a peculiar hybrid of strongly coupled matter and light waves. The condensate with its large optical density creates a substantial refractive medium for the light field; meanwhile, the cavity field exerts significant mechanical forces on the motion of the atom cloud. If the resonator is driven by a laser beam from the side, a normal-superradiant phase transition can be observed that is analogous to that of the Dicke model [1,2]. One of the collective excitations of the system soften at the phase transition [3,4] which signals a superfluid-supersolid phase transition. This polariton type excitation has finite lifetime due to photon loss, and as we show, also due to the decay into one-particle excitations. The different damping mechanisms change the character of the criticality of the phase transition.

References

[1] D. Nagy, G. Konya, G. Szirmai, P. Domokos, Phys. Rev. Lett. **104**, 130401 (2010).
[2] K. Baumann, C. Guerlin, F. Brennecke, T. Esslinger, Nature **464**, 1301 (2010).
[3] D. Nagy, G. Szirmai, P. Domokos, European Physical Journal D **48**, 127 (2008).
[4] R. Mottl, F. Brennecke, K. Baumann, R. Landig, T. Donner, T. Esslinger, arXiv:1203.1322 (2012).

Information flow and memory effects in open quantum systems

Bi-Heng Liu[1], Li Li[1], Yun-Feng Huang[1], Chuan-Feng Li[1], Guang-Can Guo[1],
Elsi-Mari Laine[2,*], Heinz-Peter Breuer[3], and Jyrki Piilo[2]

1. Key Laboratory of Quantum Information, University of Science and Technology of China
2. Turku Centre for Quantum Physics, Department of Physics and Astronomy, University of Turku
3. Physikalisches Institut, Universität Freiburg
**emelai@utu.fi*

Realistic quantum mechanical systems are always exposed to an external environment. The presence of the environment is often considered to give rise to a Markovian process in which the quantum system loses information to its surroundings. However, many quantum systems exhibit a non-Markovian behavior in which there is a flow of information from the environment back to the open system, signifying the presence of quantum memory effects [1]. The environment is usually composed of a large number of degrees of freedom difficult to control and the efficient exploitation of reservoir engineering techniques require a method for distinguishing between diverse types quantum noise by observing the open system only. We report an experiment in which we are able to control the environment and to monitor the noise through quantifying the non-Markovianity in the dynamics of the open system [2].

References

[1] H.-P. Breuer, E.-M. Laine and J. Piilo, Phys. Rev. Lett. **103**, 210401 (2009).
[2] B.-H. Liu, L. Li, Y.-F. Huang, C.-F. Li, G.-C. Guo, E.-M. Laine, H.-P. Breuer and J. Piilo, Nature Physics **7**, 931-934 (2011).

Quantum feedback experiments stabilizing Fock states of light in a cavity

Igor Dotsenko[1,*], Clément Sayrin[1], Xingxing Zhou[1], Bruno Peaudecerf[1],
Théo Rybarczyk[1], Sébastien Gleyzes[1], Michel Brune[1], Jean-Michel Raimond[1],
and Serge Haroche[1,2]

1. Laboratoire Kastler-Brossel, ENS, UPMC-Paris 6, CNRS, 24 rue Lhomond, 75005 Paris, France
2. Collège de France, 11 place Marcellin Berthelot, 75005 Paris, France
**dotsenko@lkb.ens.fr*

We report on the realization of two quantum feedback schemes allowing for the preparation and stabilization of photon-number (Fock) states of a microwave field stored in a high-Q superconducting cavity. Repetitive quantum non-demolition (QND) measurement with dispersive Rydberg atoms provides a real-time information on the field's state. Coherent microwave injection into the cavity mode [1] or individual atoms resonantly emitting or absorbing single photons from it [2] are then carefully chosen to steer in a feedback loop the field towards a desired state. Moreover, each decoherence-induced quantum jump of the field is detected by the QND sensors and then successfully corrected.

References

[1] C. Sayrin, I. Dotsenko, X. Zhou, B. Peaudecerf, T. Rybarczyk, S. Gleyzes, P. Rouchon, M. Mirrahimi, H. Amini, M. Brune, J. M. Raimond, and S. Haroche, *Real-time quantum feedback prepares and stabilizes photon number states*, Nature (London) **477**, pp. 73-77 (2011).
[2] X. Zhou, I. Dotsenko, B. Peaudecerf, T. Rybarczyk, C. Sayrin, S. Gleyzes, J. M. Raimond, M. Brune, and S. Haroche, *Field locked to Fock state by quantum feedback with single photon corrections*, accepted for publication in Phys. Rev. Lett.

Cavity QED with atomic mirrors

Darrick Chang[1,*], Liang Jiang[2], Alexey Gorshkov[2], and Jeff Kimble[2,3]

1. ICFO - Institut de Ciences Fotoniques, Castelldefels (Barcelona), Spain
2. Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, CA, USA
3. Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, CA, USA
**darrick.chang@icfo.es*

A promising approach to merge atomic systems with scalable photonics has emerged recently, which consists of trapping cold atoms near tapered nanofibers. Here, we describe a novel technique to achieve strong, coherent coupling between a single atom and photon in such a system [1]. Our approach makes use of collective enhancement effects, which allow a lattice of atoms to form a high-finesse cavity in the fiber. Under realistic conditions, one can attain the "strong coupling" regime of cavity QED, wherein it becomes feasible to observe vacuum Rabi oscillations between a specially designated "impurity" atom within the cavity and a single cavity quantum. This mechanism can form the basis for a scalable quantum network using atom-nanofiber systems. We also describe novel correlations that arise in this system between light and atomic positions and momenta.

Reference

[1] D. E. Chang, L. Jiang, A. V. Gorshkov, and H. J. Kimble, *Cavity QED with atomic mirrors*, arXiv e-prints 1201.0643 (2012).

Two component superluminal light

N. Bezuglov[1,2,*], A. Ekers[1], J. Ruseckas[3], V. Kudriašov[3], and G. Juzeliūnas[3]

1. Laser Centre, University of Latvia, Riga, Latvia
2. Faculty of Physics, St. Petersburg State University, St. Petersburg, Russia
3. Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania
**bezuglov@NB16672.spb.edu*

In the last decades there was an interest in superluminal light, that is light pulses with the group velocity larger than the speed of light in vacuum. Experimental and theoretical schemes were provided for realization of one-component [1] andtwo-component [2] superluminal light pulses employing a gain media. In the scheme proposed in [2] two superluminal pulses are not symmetrical: the seed pulse generates a much weaker conjugated pulse. We suggest an alternative scheme for two-component superluminal light, which is an extension of the scheme proposed in [1]. Instead of one gain doublet and one probe field we use two gain doublets and two probe fields. The main advantage of such a scheme is the flexibility in controlling the two superluminal pulses by changing parameters of the gain doublets.

This work was carried out within the EU FP7 Centre of Excellence FOTONIKA-LV, the EU FP7 IRSES Project COLIMA, a trilateral grant of Latvian, Lithuanian, and Taiwanese Research Councils.

References

[1] L. J. Wang, A. Kuzmich, and A. Dogariu, *Gain-assisted superluminal light propagation*, Nature **406**, pp. 277-279 (2000).
[2] R. T. Glasser, U. Vogl, and P. D. Lett, *Stimulated generation of superluminal light pulses via four-wave mixing*, PRL **108**, pp. 173902,1-5 (2012).

Dissipative many-body quantum optics in Rydberg media

Alexey V. Gorshkov[1], Rejish Nath[2], Johannes Otterbach[3], Michael Fleischhauer[4], Mikhail D. Lukin[3], and Thomas Pohl[5]

1. Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA
2. IQOQI and Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria
3. Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA
4. Fachbereich Physik und Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany
5. Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany
**avgorshkov@gmail.com*

We develop the theory of light propagation under the conditions of electromagnetically induced transparency in systems involving strongly interacting Rydberg states. Taking into account the quantum nature of light, we compute the propagation of an arbitrary input pulse in the limit of strong Rydberg-Rydberg interactions. We also solve the case of a few-photon pulse for arbitrary Rydberg-Rydberg interaction strengths [1]. We show that this system can be used for the generation of nonclassical states of light including single photons and trains of single photons with an avoided volume between them, for implementing photon-photon gates, as well as for studying many-body phenomena with strongly correlated photons.

Reference

[1] A. V. Gorshkov, J. Otterbach, M. Fleischhauer, T. Pohl, and M. D. Lukin, *Photon-Photon Interactions via Rydberg Blockade*, Phys. Rev. Lett. **107**, 133602 (2011).

Engineering a non-Gaussian quantum state of an atomic ensemble

S. Lund Christensen, J. B. Béguin, H. Lundgaard Sørensen, J. Appel, and E. S. Polzik

QUANTOP, Niels Bohr Institute, University of Copenhagen, Denmark

We report on our progress towards engineering a collective, non-Gaussian quantum state in an ensemble of dipole-trapped Cs atoms. Such states are an important prerequisite for continuous variable quantum information processing and can be a valuable resource for quantum metrology applications [1]. Our experimental apparatus is described in [2]. We start by preparing all atoms in the $|\uparrow\rangle = |F=4, m_F=0\rangle$ clock state and apply a weak excitation pulse, resonant with the $|F=4, m_F=0\rangle \to |F'=4, m'_F=+1\rangle$ transition. Conditioned on the detection of a single forward-scattered photon of the right energy and polarization we know that with a probability of > 2/3 a single atom has been scattered into the lower $|\downarrow\rangle = |F=3, m_F=0\rangle$ clock level and the collective quantum state of the example is now described by $|\psi\rangle = \sum_{i=1}^{N_a} |\uparrow\uparrow \cdots \uparrow\downarrow_i \uparrow \cdots \uparrow\rangle$. We then apply a microwave $\pi/2$-pulse to make the single atom interfere with the remaining $F = 4$–atoms. By performing quantum non-demolition measurements of the atomic population difference in the clock-levels using a dispersive dual-color probing-scheme we obtain marginal statistics of the non-Gaussian Wigner function of this state and we compare our result with the Gaussian Wigner function of a coherent spin state.

References

[1] J. I. Cirac *et al.*, Phys. Rev. Lett. 78, 32213224 (1997), N. Brunner *et al.* Phys. Rev. A. 84, 041804(R) (2011), M. Ohliger *et al.*, Phys. Rev. A 82, 042336 (2010).
[2] A. Louchet-Chauvet *et al.*, New J. Phys. 12 065032 (2010).

Photoluminescence of exciton polariton condensates at high densities

Natsuko Ishida[1,*], Tim Byrnes[2], Tomoyuki Horikiri[2], and Yoshihisa Yamamoto[2,3]

1. Advanced Science Institute, RIKEN, Japan
2. National Institute of Informatics, Japan
3. c Edward L. Ginzton Laboratory, Stanford University, Stanford California, USA
**Corresponding author: n_ishida@riken.jp*

Exciton-polariton condensates need to be continuously pumped due to their short lifetime of the order of picoseconds. This open-dissipative nature of the system is particularly important in the high density regime, bringing new physics beyond traditional atomic BEC systems: the gain and loss of the condensate can no longer be ignored.

At high density, it has been a controversial issue of whether exciton-polariton BECs would undergo a crossover to photon lasing based on electron-hole plasma, or an electron-hole BCS-like phase [1-3]. In this work we discuss the property of the high density exciton-polariton BECs via two-time correlation function of an open system [4] taking into account of reservoir pumping and cavity, exciton loss. We consider a model where the lower polaritons are pumped into the condensate and decay with the finite lifetime. We also consider effects of a time dependent pump, which more closely simulates the experimental situation where a pulsed excitation is used.

References

[1] P. Eastham and P. Littlewood, Phys. Rev. B 64, 235101 (2001).
[2] J. Keeling *et al.*, Phys. Rev. B **72**, 115320 (2005).
[3] T. Byrnes *et al.*, Phys. Rev. Lett. **105**, 186402 (2010).
[4] J. I. Perea *et al.*, Phys. Rev. B 70, 115304 (2004).

Transfer of spin squeezing and particle entanglement between atoms and photons in coupled cavities via two-photon exchange

Ali Ü. C. Hardal and Özgür E. Müstecaplıoğlu*

Department of Physics, Koç University, Sarıyer, Istanbul, 34450, Turkey
**omustecap@ku.edu.tr*

We consider a system of two optical cavities coupled via two-photon exchange [1]. Each cavity contains a single atom interacting with cavity photons with a two-photon cascade transition. Characterizing both particle entanglement and spin squeezing by optimal spin squeezing inequalities, we examine their transfers between photonic and atomic subsystems for initially separable and entangled two-photon cases. It is observed that particle entanglement is first generated among the photons and then transferred to the atoms. The inter-cavity two-axis twisting spin squeezing interaction, induced by two-photon exchange, is revealed itself as engendering physical mechanism. The effect of the local atom-photon interactions on the trasfer of spin squeezing and entanglement is pointed out by being compared with the non- local two-photon exchange.

Reference

[1] M. Alexanian, *Two-photon exchange between two three-level atoms in separate cavities*, Phys. Rev. A **83**, 023814 (2011).

Demonstration of the interaction between two stopped light pulses

Yi-Hsin Chen[1], Meng-Jung Lee[1], Weilun Hung[1], Ying-Cheng Chen[2,1], Yong-Fan Chen[3], and Ite A. Yu[1,*]

1. Department of Physics and Frontier Research Center on Fundamental and Applied Sciences of Matters, National Tsing Hua University, Hsinchu 30013, Taiwan
2. Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 10617, Taiwan
3. Department of Physics, National Cheng Kung University, Tainan 70101, Taiwan
**yu@phys.nthu.edu.tw*

The efficiency of a nonlinear optical process is equal to the product of the transition rate and interaction time. If the interaction time can be maximized, it is possible to achieve high efficiency even below single-photon level. Based on the techniques of stored light and stationary light, we report the first experimental demonstration that two light pulses were made motionless and interacted with each other through a medium [1]. To demonstrate the enhancement of optical nonlinear efficiency, we used the process of one optical pulse switched by another. Our result shows that motionless light pulses can activate switching at 0.56 photons per atomic absorption cross section. The great potential of the scheme is that the switching efficiency is not limited to the present result but can be further improved by increasing the optical density of the medium. This work advances the technology of low-light-level nonlinear optics and quantum information manipulation utilizing photons.

Reference

[1] Y. H. Chen, M. J. Lee, W. Hung, Y. C. Chen, Y. F. Chen, and I. A. Yu, Phys. Rev. Lett. **108**, 173603 (2012).

Deterministic photon pairs via coherent optical control of a quantum dot

H. Jayakumar[1], A. Predojević[1,*], T. Huber[1], T. Kauten[1], G. S. Solomon[2], and G. Weihs[1,3]

1. Institute for Experimental Physics, University of Innsbruck, Innsbruck, Austria
2. Joint Quantum Institute, National Institute of Standards and Technology & University of Maryland, Gaithersburg, USA
3. Institute for Quantum Computing, University of Waterloo, Ontario, Canada
**ana.predojevic@uibk.ac.at*

We report on the atom-like coherent control of a single self-assembled InAs quantum dot. In particular, we resonantly drive Rabi oscillations between the ground and the biexciton state via two-photon excitation. A π-pulse deterministically populates the biexciton state which then decays in a biexciton-exciton cascade. Full coherent control of the excitation process is proven by the observation of Ramsey fringes. This is the first demonstration of coherently created photon pairs from a single self-assembled InAs quantum dot as well as the first demonstration of an extension of the coherence time of an excitonic qubit with an all-optical echo technique.

The resonant creation of the photon pairs completely suppresses multi-photon emission which is a unique feature of this excitation scheme. Deterministic coherent excitation makes this system well suitable for schemes like time-bin entanglement or probabilistic interaction of the photons originating from dissimilar sources.

Single photon Kerr effect: observing coherent state revivals

Brian Vlastakis[1,*], Gerhard Kirchmair[1], Hanhee Paik[1], Simon Nigg[1], Luigi Frunzio[1]
Mazyar Mirrahimi[1,2], Steven Girvin[1], Michel Devoret[1], and Robert Schoelkopf[1]

1. Department of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA
2. INRIA Paris-Rocquencourt, Domaine de Voluceau, B.P. 105, 78153 Le Chesnay Cedex, France
**brian.vlastakis@yale.edu*

Circuit Quantum Electrodynamics provides a new regime of cavity QED where interaction strengths are many times larger (> 1000) than system losses. Utilizing a superconducting transmon qubit, we are able to induce Kerr non-linearities in a three-dimensional cavity resonator which are 20 times larger than its characteristic cavity decay. This regime allows us to observe the apparent dephasing and subsequent refocusing of a coherent state due to the Kerr interaction. Throughout this process, the coherent state will naturally evolve into multi-component Schrödinger cat states before refocusing. Using cavity state tomography, we are able to measure these non-classical states of light and observe coherent state revivals.

Multi-spatial-mode quadrature squeezing

Plamen G. Petrov*, Matthew Turnbull, and Vincent Boyer

School of Physics and Astronomy, University of Birmingham, Edgbaston, B15 2TT, UK
**p.g.petrov@bham.ac.uk, v.boyer@bham.ac.uk*

We present a method to generate a beam of light with amplitude fluctuations below the standard quantum limit across multiple spatial sidebands. Four-wave-mixing in hot Rubidium vapour has previously been shown to generate twin beams that demonstrate quantum correlations in spatially correlated regions, that is to say quadrature entanglement between multiple transverse spatial modes [1]. The next step combines these beams in a single beam with quadrature squeezing across an equal number of transverse modes. Effectively, this means that the beam presents reduced quantum amplitude fluctuations *localy* at any point of the beam tranverse profile.

We describe the theory underlying this process along with our first experimental results, and possible applications of the generated multi-spatial-mode squeezed light, e.g. super-resolution imaging beyond the standard quantum limit.

Reference

[1] V. Boyer *et al.*, *Entangled Images from Four-Wave Mixing*, Science **321**, pp. 544-547 (2008).

A state-insensitive, compensated nanofiber trap

A. Goban[1, *], K. S. Choi[1,2], D. J. Alton[1], D. Ding[1], C. Lacroute[1], M. Pototschnig[1]
J. A. M. Silva[1], C. L. Hung[1], T. Thiele[1], N. P. Stern[1], and H. J. Kimble[1]

1. Quantum Optics Group, California Institute of Technology, Pasadena, CA, USA
2. Spin Convergence Research Center, Korea Institute of Science and Technology, Seoul, Korea
**agoban@caltech.edu*

An exciting frontier in QIS is the integration of quantum elements into quantum networks [1]. Single atoms and atomic ensembles endow quantum functionality and the capability to build quantum networks. Following the realization of a nanofibertrap [2], we have implemented an optical trap that localizes single Cs atoms ≃ 215 nm from surface of a nanofiber [3]. By operating at magic wavelengths for counter-propagating red- and blue-detuned trapping beams, differential scalar light shifts are eliminated, and vector shifts are suppressed by ≃ 250. We measure an absorption linewidth $\Gamma/2\pi = 5.7 \pm 0.1$ MHz for the Cs $6S_{1/2}, F=4 \rightarrow 6P_{3/2}, F'=5$ transition, where $\Gamma_0/2\pi = 5.2$ MHz in free space, and an optical depth of $d \simeq 66$, corresponding to $d_1 \simeq 0.08$ per atom. The bandwidth for reflection from the 1D array scales linearly with the entropy for the multiplicity of trapping sites. These advances provide an important capability for quantum networks and precision atomic spectroscopy near dielectric surfaces.

References
[1] H. J. Kimble, *The Quantum Internet*, Nature **453**, 1023 (2008).
[2] E. Vetsch *et al.*, Phys. Rev. Lett. **104**, 203603 (2010).
[3] A. Goban*, K. S. Choi*, D. J. Alton*, D. Ding, C. Lacroute, M. Pototschnig, T. Thiele, N. P. Stern, H. J. Kimble, arXiv.1203.5108 (2012).

Proposal for ion trap bosonic simulator

Hoi Kwan Lau* and Daniel F. V. James

Department of Physics, University of Toronto, Toronto, Canada
**hklau@physics.utoronto.ca*

We propose two architectures to implement bosonic simulators using ion trap system. The first approach employs a linear array of ions trapped in a single harmonic well. Bosonic information can be encoded on the collective phonon modes of the trapped ions. Single mode operation is conducted by sideband transition; linear beam splitter can be implemented by Raman interaction. The second approach simulates bosonic modes by the motional modes of individually trapped ions. Single mode linear operators, nonlinear phase operator, and linear beam splitter can be simulated by precisely controlling the trapping potentials. All the processes in this approach can be conducted beyond the Lamb-Dicke regime. In both architectures, quantum information can be extracted by adiabatic transfer, post-selection, or sideband transition. Interesting linear bosonic phenomena, such as the Hong-Ou-Mandel effect, can be implemented by today's technology.

Effects of interactions on the quasiperiodic kicked rotor metal-insulator transition

Benoît Vermersch[1], Dominique Delande[2], and Jean Claude Garreau[1,*]

1. Laboratoire de Physique des Lasers, Atomes et Molécules, Université Lille 1, France
2. Laboratoire Kastler-Brossel, UPMC-Paris 6, France
**http://www.phlam.univ-lille1.fr/atfr/cq*

In a disordered potential, the diffusive transport of non-interacting particles can be inhibited by quantum interference effects, a phenomenon known as Anderson localization [1]. In 3 dimensions, there exists a quantum phase-transition between localized (insulator) and diffusive (metal) dynamics. A long-standing question is the effect of interactions on such dynamics. We investigated this problem numerically using a "quantum simulator" of the 3D Anderson model, the quasiperiodic kicked rotor, recently used for precise experimental measurements of the critical exponent [2]. Interactions are included using a mean-field approximation, and their effect on the phase-transition quantified: Interactions progressively shift the corresponding critical exponent from 1.6 (corresponding to the orthogonal universality class) to 1, characteristic of the self-consistent theory of the Anderson transition. For strong enough interactions, multifractality is transitorily suppressed.

References

[1] P. W. Anderson, Phys. Rev. **109**, 1492 (1958).
[2] J. Chabé *et al.*, Phys. Rev. Lett. **101**, 255702 (2008) ; M. Lopez *et al.*, Phys. Rev. Lett. **108**, 095701 (2012).

Spin-orbit coupling induced instability of Raman dressed states

Jin-Yi Zhang[1], Long Zhang[1], Si-Cong Ji[1], Zhi-Dong Du[1], You-Jin Deng[1], Hui Zhai[3], Peng Zhang[2], Shuai Chen[1,*], and Jian-Wei Pan[1,*]

1. Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230027, China
2. Department of Physics, Renmin University of China, Beijing 100872, China
3. Institute for Advanced Study, Tsinghua University, Beijing, 100084, China
**shuai@ustc.edu.cn, pan@ustc.edu.cn*

Spin-orbit coupling brings distinctive character to Raman-dressed ultra-cold atom systems. In this work, we systemically study the decay behavior of a spin-orbit coupled Bose-Einstein condensate of ^{87}Rb atoms prepared in a metastable dressed state, and quantitatively examine the respective effects of two underlying decay mechanisms: single-atom spatial motion and two-atom collision. The agreement between experimental results and theoretical calculations strongly support the statement that the spin-orbit-coupling-induced decay is generally dominated by two-atom collisions. Our work would be helpful for both experimental simulations involving metastable dressed states and dark state with spin-orbit coupling.

Flux lattices and topological flat bands in dipolar spin systems

Norman Y. Yao[1,*], Chris Laumann[1,2], Alexey V. Gorshkov[3], Steven D. Bennett[1]
Peter Zoller[4], and Mikhail D. Lukin[1]

1. Physics Department, Harvard University, Cambridge, MA, USA
2. ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
3. Institute for Quantum Information, California Institute of Technology, Pasadena, CA, USA
4. IQOQI of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria
**nyao@fas.harvard.edu*

Topological flat bands provide a fascinating route to the realization of fractional topological insulators and anomalous quantum hall states. Here, we provide the first microscopic description of a physical system, which naturally realizes such bands. In particular, we consider a generic two-dimensional lattice system of tilted, interacting dipoles and demonstrate that such a system harbors single-particle bands with non-trivial topology as well as a quenched kinetic energy relative to the interaction scale. Moreover, we demonstrate that such systems naturally enable uniform arbitrary π / N (for all $N \in \mathbb{Z}$) flux per plaquette, allowing for the realization of a high-field fractional quantum Hall regime where the flux quanta per lattice cell is large. We propose an experimental realization with polar molecules in optical lattices.

Rydberg crystals

R. M. W. van Bijnen*, S. Smit, E. J. D. Vredenbregt, and S. J. J. M. F. Kokkelmans

Eindhoven University of Technology, The Netherlands
**r.m.w.v.bijnen@tue.nl*

Ultracold atomic gases provide a rich playground for realising textbook examples of condensed matter phenomena. A recent novel direction is the creation of crystalline structures of highly excited Rydberg atoms, which can be a model for dilute metallic solids with tunable parameters, and provide access to the regime of strongly coupled systems. In practice, crystal creation is made difficult by the ’Rydberg blockade’, where one atom in the Rydberg state shifts the energy levels of thousands of its neighbours out of resonance with the excitation laser. By careful shaping of the excitation laser pulse, we exploit the blockade effect and show how to create large, crystalline structures [1].

Reference

[1] R. M. W. van Bijnen, S. Smit, K. A. H. van Leeuwen, E. J. D. Vredenbregt, S. J. J. M. F. Kokkelmans, *Adiabatic formation of Rydberg crystals with chirped laser pulses*, J. Phys. B: At. Mol. Opt. Phys. 44 184008 (2011).

Optical lattice based quantum simulators for relativistic field theories

Nikodem Szpak

Universität Duisburg-Essen, Germany
nikodem.szpak@uni-due.de

We show how (discretized) relativistic field theories emerge from the low energy regime of optical lattice systems loaded with ultra-cold atoms. In particular, we demonstrate a general mechanism of mass generation on the lattice and the apearance of pseudo-relativistic energy-momentum relation for quasi-particles, known for several particular systems. Our goal is to present the underlying mechanisms from a unified perspective, applicable for general Hubbard-like Hamiltonian systems, including also crystalline materials like graphene. We complete by giving examples in different geometric settings.

References

[1] N. Szpak and R. Schützhold, Phys. Rev. A **84**, 050101(R) (2011).
[2] N. Szpak and R. Schützhold, New J. Phys. 14 (2012) 035001.

Collisions involving nD + nD Rydberg states in a dipole trap

Jader Cabral*, Jorge K. Massayuki, Luis F. Gonçalvez, and Luis G. Marcassa

Laboratory of Atomic Interaction - IFSC, University of São Paulo, Brazil
**jscabral@ursa.ifsc.usp.br*

We have studied nD + nD multilevel pairwise interactions between Rydberg atoms in a magneto-optical trap, and our results have shown that the electric field plays an essential role in the interaction dynamic [1,2]. In this work, our goal is to study the nD + nD interaction in a higher density cold sample in a dipole trap. Therefore, we have loaded a QUEST trap for Rb using a CO_2 laser. The dipole laser beam is focused to a spot size ($1/e^2$) around 70 μm. For 75 W laser power, the QUEST depth is ~ 730μK and the density sample is arround 4×10^{11} atoms/cm^3. The nD Rydberg states are excited using a CW blue light (480nm) with 1MHz of linewidth. During the presentation we will show our first results on the nD + nD interactions in a CO_2 optical trap.

References

[1] J. S. Cabral *et al.*, "Effects of electric fields on ultracold Rydberg atom interactions", J. Phys. B: At. Mol. Opt. Phys. 44 (2011) 184007 (12pp).
[2] J. S. Cabral *et al., "*Manipulation of quantum state transfer in cold Rydberg atom collisions", New J. Phys. 12 09302(2010).

A system to study anisotropy in interactions between cold Rydberg atoms

Jorge D. M. Kondo*, Luís F. L. Gonçalves, Jader S. Cabral, and Luís G. Marcassa

Laboratório de Interações Atômicas (LIA),USP/Universidade de São Paulo, São Paulo, Brasil
massayukikondo@ursa.ifsc.usp.br

The comprehension of interactions between cold Rydberg atoms plays an important role on quantum computing experiments using such atoms. Stray electrical fields are common in different types of atomic traps, and may lead to decoherences [1] and anisotropies. Recently, our group has built a new setup to study Rydberg interactions using a QUEST optical dipole trap to confine neutral rubidium atoms. The Rydberg atoms are excited from the 5P state using a CW homemade second harmonic generation system at 480 nm. An elaborated system of metallic plates and bars allow us to control very well the value and direction of an external electric field at atomic trap, which allows us to define a quantization axis for the collisions. Our goal is to study the anisotropy of nD+nD collisions in this system as a function of the angle between the electric field and the collisional axis. Preliminary results will be present.

Reference

[1] J. S. Cabral, J. M. Kondo, L. F. Gonçalves, V. A. Nascimento, L. G. Marcassa, D. Booth, J. Tallant, A. Schwettmann, K. R. Overstreet, J. Sedlacek and J. P. Shaffer, "Effects of electric fields on ultracold Rydberg atom interactions", Journal of Physics B: Atomic, Molecular and Optical Physics, v. **4**, pp. 184007 (2011).

Near-threshold Feshbach resonances

Frauke Schwarz, Tim-Oliver Müller, and Harald Friedrich*

Physik Department, Technische Universität München, Garching, Germany
**harald.friedrich@tum.de*

The formula $a = a_{\mathrm{bg}}\left[1 + \Delta B / (B - B_0)\right]$ is often used to describe the pole singularity of the scattering length a when a Feshbach resonance is tuned across the threshold of an atom-atom potential by varying the strength B of an external field [1, 2]. The parameters a_{bg}, B_0 and ΔB are to some extent inter- dependent and their relation to the underlying properties in the open and the closed channel is not clear.

The following universally valid formula [3] for the scattering length transparently identifies properties of the uncoupled open channel and the effects arising from coupling to the closed channel:

$$a = \left[a_{\mathrm{bg}} + \frac{\bar{\Gamma}/2}{E_{\mathrm{R}}}\left(\bar{a}\frac{a_{\mathrm{bg}} - \bar{a}}{b} - b\right)\right]\left[1 + \frac{\bar{\Gamma}/2}{E_{\mathrm{R}}}\left(\frac{a_{\mathrm{bg}} - \bar{a}}{b}\right)\right]^{-1}.$$

$a_{\mathrm{bg}} \in (-\infty, +\infty)$ is the scattering length of the uncoupled open channel; $\bar{a}$ and b are invariant lengths depending only on the open channel's potential tail; E_{R} is the resonance position, which can be tuned, e.g. as function of B, while $\bar{\Gamma}$ is an energy-independent width due to the channel coupling.

References

[1] C. Chin, R. Grimm, P. Julienne and E. Tiesinga, Rev. Mod. Phys. **82**, pp. 1225-1286 (2010).
[2] A. J. Moerdijk, B. J. Verhaar and A. Axelsson, Phys. Rev. A **51**, pp. 48524861 (1995).
[3] F. Schwarz, T.-O. Müller and H. Friedrich, submitted to Phys. Rev. A.

Quantum mixtures of lithium and ytterbium atoms

A. H. Hansen*, A. Khramov, A. Jamison, W. Dowd, B. Plotkin-Swing, and S. Gupta

University of Washington, Seattle, USA
**ahhh@washington.edu*

Mixtures of alkali and spin-singlet atoms offer new studies of few- and many-body physics, and a starting point for producing paramagnetic polar molecules. We have recently produced quantum degenerate mixtures of lithium (alkali) and ytterbium (spin-singlet) atoms [1, 2]. Here we investigate a three-component mixture of bosonic ^{174}Yb atoms and two resonantly-interacting, fermionic ^{6}Li spin states. We observe dynamics of $^{6}Li_2$ Feshbach molecule formation and decay, as modified by a third, non-resonant component, and find remarkable molecule stability even in the absence of Fermi statistics, with a dominance of elastic interactions at unitarity. In a separate study, we demonstrate species-selective spatial control of ^{6}Li and ^{174}Yb, using magnetic field gradients. This technique can mitigate differential gravitational sag in mass-imbalanced mixtures, and may realize a spatially-resolved, microscopic probe. Finally, we report on progress towards forming the paramagnetic polar molecule LiYb.

References

[1] V. Ivanov et. al., *Sympathetic Cooling in an Optically Trapped Mixture of Alkali and Spin-Singlet Atoms*, Phys. Rev. Lett. **106**, 153201 (2011).
[2] A. H. Hansen et. al., *Quantum Degenerate Mixture of Ytterbium and Lithium Atoms*, Phys. Rev. A **84**, 011606(R) (2011).

Dicke modelling of many-body interactions in a cold Rydberg gas

P. Huillery[1,2,3,*], M. Viteau[3], M. G. Bason[3], N. Malossi[3,4], D. Ciampini[2,3,4], O. Morschpt[3], E. Arimondo[2,3,4], D. Comparat[1], and P. Pillet[1]

1. Laboratoire Aimé Cotton, Université Paris-Sud 11, Campus d'Orsay Bat. 505, 91405 Orsay, France
2. Dipartimento di Fisica 'E. Fermi', Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy
3. INO-CNR, Largo Pontecorvo 3, 56127 Pisa, Italy
4. CNISM UdR, Dipartimento di Fisica 'E. Fermi', Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy
**paul.huillery1@u-psud.fr*

Atoms excited to Rydberg states are highly polarizable and, therefore, can interact strongly with each other at large distances, via dipole or van-der-Waals interactions. These interactions make them attractive candidates for studies of strongly correlated systems and the implementation of quantum logic gates. A key signature of interactions between Rydberg atoms is the suppression of fluctuations of the dipole-blockaded excitations, that we have investigated in a R bMOT. Because a quantum mechanical treatment containing the states of all the atoms in a MOT is not feasible, our results are analysed using an original theoretical model based on the well established Dicke model of quantum optics. The Dicke model is modified by including the van der Waals interactions between the Dicke collective states. This approach leads to a manageable size of the basis set for the simulations. The Dicke state model includes statistical fluctuations and hence gives access to the complete counting statistics, in particular the measured variance of the Rydberg excitations.

This work was supported by the E.U. through grant No. 265031-ITN-COHERENCE and the collaboration between University of Pisa and University of Paris Sud-11.

Study of mesoscopic clouds of cold atoms in the interacting regime

Ronan Bourgain, Joseph Pellegrino, Andreas Fuhrmanek,
Yvan R. P. Sortais*, and Antoine Browaeys

Laboratoire Charles Fabry, Groupe Optique Quantique - Equipe Atomes,
Institut d'Optique, 2 Avenue Augustin Fresnel, 91127 Palaiseau Cedex, France
**yvan.sortais@institutoptique.fr*

We present studies on cold and dense atomic ^{87}Rb clouds containing $N \sim 2 - 100$ interacting atoms. We produced such mesoscopic ensembles by loading a microscopic optical dipole trap from a MOT. Due to 2-body light-assisted collisions, we have found that in steady state such ensembles exhibit reduced number fluctuations with respect to a Poisson distribution. For $N \geq 2$, we measured a reduction Fano factor $F = 0.72 \pm 0.07$ consistent with the value $F = 3/4$ predicted at large N by a general stochastic model [1, 2]. To enhance interactions between the atoms, we are following two tracks. Firstly we evaporatively cooled a few hundreds of trapped atoms and obtained $\sim$ 10 atoms close to quantum degeneracy ($n\lambda_{dB}^3 \sim 1$) in the microscopic trap. In this regime s-wave interactions dominate ($n = 2 \times 10^{14}$ at.cm^{-3}). Secondly we sent near resonant light at a wavelength λ_p on the small cloud (size l). When $l < \lambda_p/2\pi$, dipole-dipole interactions should lead to collective behaviour.

References

[1] A. Fuhrmanek, Y. R. P. Sortais, P. Grangier, A. Browaeys, *Measurement of the atom number distribution in an optical tweezer using single photon counting*, Phys. Rev. A **82**, 023623 (2010).
[2] Y. R. P. Sortais, A. Fuhrmanek, R. Bourgain, A. Browaeys, *Sub-Poissonian atom number fluctuations using light-assisted collisions*, Phys. Rev. A **85**, 035403 (2012).

Creating and probing photonic molecules: a progress report

Rafael R. de Paiva[1,*], Edwin Pedrezo-Peñafiel[1,*], Franklin J. Vivanco[1], Yehuda B. Band[2], Kilvia M. Farias[1],
and Vanderlei S. Bagnato[1]

1. Instituto de Física de São Carlos, Universidade de São Paulo- SP, Brasil
2. Department of Chemistry and Electro-Optics, Ben-Gurion University, Israel
**rothganger@gmail.com*

In this work we describe different effects of two-photon interaction with cold colliding atoms. The first effect is related to two-photon cooperative absorption, which is being presented in another contribution [1, 2]. The second effect is related to a new way of creating bound states using two-photon atom interaction. The idea is that during a collision of two sodium atoms, occurs a two, distinguishable, photon interaction. The first (second) absorption of a red (blue) detuned photon connecting the pair ground state ($3S_{1/2}$+$3S_{1/2}$) to the attractive (repulsive) part of the quasi-molecular level ($3S_{1/2}+3P_{3/2}$). If the light fields are strong enough the atoms will be dressed by the two photons, creating a molecular bound state which is completely dependent of the light fields. Following calculations, of the shape of the potential, we have studied the role of the attractive and repulsive channels present in the processes, as well as made the first attempt to detect those bound states.

References

[1] E. Pedrezo-Peñafiel, R. R. Paiva, F. J. Vivanco, V. S. Bagnato and K. M. Farias "Two-photon cooperative absorption in colliding cold Na", Physical Review Letter. Not yet publish.
[2] Kilvia M. Farias Poster.

Very low-energy metastablity exchange in Argon studied by a pulsed merging beam technique

T. Taillandier-Loize[1,*], M. Hamamda[1], F. Perales[1], G. Dutier[1], V. Bocvarski[2], J. Baudon[1], and M. Ducloy[1]

1. Laboratoire de Physique des Lasers (UMR-CNRS 7538), Université Paris 13, 99 Av. J.B. Clément, 93430-Villetaneuse, France
2. Institute of Physics - Belgrade, Pregrevica 118, 11080-Zemun, Serbia
**thierry.taillandier-loize@univ-paris13.fr*

The resonant metastability exchange between co-propagating polarized metastable atoms Ar* ($^3P_2$, M = +2) and ground state atoms of a nozzle beam, at centre-of-mass energies ranging from 0.9 to 5 meV, is investigated using a pulsed regime and a time-of-flight technique. Polarized metastable atoms are slightly slowed down by the transient effect of a Zeeman slower driven by an acousto-optic modulator. Very low centre-of-mass energies are accessible owing to the "kinematical contraction" usually realized in merging beam experiments [1,2]. Owing to a chopper disk holding 2 neighbouring slits, 2 successive packets F_1, F_2 of fast ground state atoms Ar (velocity v_0) and 2 packets S_1, S_2 of slow metastable atoms Ar* (velocity v*) are prepared. The delay is such that atoms Ar of F_2 overtake atoms Ar* of S_1 before reaching the detector. The velocity of exchanged Ar* atoms passes from v* up to v_0. The process is identified by time-of-flight analysis and the total exchange cross section σ_e is derived. Theoretically σ_e involves 2g and 2u molecular potentials of the Ar_2* system [3].

References
[1] See *e.g.* K. Olamba, S. Szücs, J. P. Chenu, El Arbi Naji and F. Brouillard , J. Phys.B : At. Mol. Opt. Phys. **29**, 2837 (1996).
[2] J. Grucker *et al.*, J. Phys.B : At. Mol. Opt. Phys. **41**, 021001 (2008).
[3] J. Robert, *Thèse de 3e Cycle,* Université Paris Sud (1982).

2D holographic optical lattices for single atoms manipulation

Lucas Béguin, Aline Vernier*, Thierry Lahaye, and Antoine Browaeys

LCFIO, Campus Polytechnique - RD 128, 91127 Palaiseau, Cedex, France
**aline.vernier@institutoptique.fr*

Two-dimensional lattices of single atoms are a promising environment allowing fine control of the atomic interactions in a mesoscopic ensemble. We propose an experiment to study the long range dipole-dipole interactions in the system working in the Rydberg blockade regime. The versatility of holographically generated 2D arrays of single atoms should allow us to achieve arbitrary geometries as well as site-to-site addressability, thus enabling the tunability of the interactions within the system.

References
[1] Y. Miroshnychenko, A. Gaëtan, C. Evellin, P. Grangier, D. Comparat, P. Pillet, T. Wilk, and A. Browaeys, "Coherent excitation of a single atom to a Rydberg state.", PRA **82**, 013405 (2010).
[2] T. Wilk, A. Gaëtan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, and A. Browaeys, "Entanglement of Two Individual Neutral Atoms Using Rydberg Blockade", PRL 104, 010502 (2010).

Intensity noise filtering via electromagnetically induced transparency

Sang Min Lee, Hee Jung Lee, and Han Seb Moon*

Department of Physics, Pusan National University, Busan 609-735, Korea
**hsmoon@pusan.ac.kr*

We report on intensity fluctuation reduction of the intensity modulated probe laser via electromagnetically induced transparency (EIT) in the $5S_{1/2}$-$5P_{1/2}$ transition of the L-type system of the ^{87}Rb atom. When the EIT was performed with the amplitude modulated probe laser, EIT spectra have been investigated as a function of the modulation frequency. As the amplitude moduation frequency of probe laser increased from 1 kHz to 50 kHz, the modulation depth in the EIT window decreased significantly compared with the lower frequency modulated EIT. The modulation amplitude reduction in the EIT window could be understood as the Fourier transformation of intensity modulation to frequency modulation. When we analyzed the RF frequency of the amplitude modulated probe laser passing through the EIT medim using a RF spectrum analyzer, the modulation freqeuncy component was reduced via the dense EIT medium. In this presentation, we show that the dense EIT medium may apply to not only optical frequency filtering but also optical amplitude filtering [1-2].

References

[1] E. E. Mikhailov, V. A. Sautenkov, Y. V. Rostovtsev, A. Zhang, M. S. Zubairy, M. O. Scully, and G. R. Welch, "Spectral narrowing via quantum coherence," Phys. Rev. **A** 74, 013807 (2006).
[2] I.-H. Bae, H. J. Lee, and H. S. Moon, "Electromagnetically induced transparency with variable fluctuation time of photon number of pseudothermal probe light," J. Opt. Soc. Am. **B** 28, 1578-1582 (2011).

Laser-controlled adsorption of atoms on dielectric surfaces

W. Soares Martins, T. Passerat de Silans*, M. Oriá, and M. Chevrollier

Laboratório de Espectroscopia Ótica, DF-CCEN, Cx. Postal 5086 - Universidade Federal da Paraíba, 58051 - 900 João Pessoa - PB, Brazil
**thierry@otica.ufpb.br*

A technique to control with laser the growth of an alkali metal film at a gas – dielectric interface has been described some years ago, which involves manipulating the atomic adsorption with light frequency near the D2 resonance of an alkali vapor [1]. Nevertheless, the physical mechanisms have not yet been understood. We describe here systematic experiments to investigate this process at the atomic level. Our results indicate that resonant three-photon ionization is a necessary step, increasing the atom-surface attraction relative to usual fluctuating dipole-induced van der Waals forces. We hope those results will help improve lithographic techniques in a gaseous environment.

Reference

[1] A. E. Afanasiev, P. N. Melentiev and V. I. Balykin, "Laser-Induced Quantum Adsorption of Atoms on a Surface", JEPT Letters, **86**, pp. 172-177 (2007).

"Exotic" magnetically tunable feshbach resonances in ultracold mixtures of open-shell and closed-shell atoms

Piotr S. Żuchowski

Instytut Fizyki, Uniwersytet Mikolaja Kopernika, Grudziadzka 5/7, 87-100 Torun, Poland
pzuch@fizyka.umk.pl

Molecules with non-zero magnetic and electric dipole moments are extremely interesting for novel applications in quantum informatics or experimental measurements of magnitude of eEDM. Obvious candidates for such molecules are mixtures of laser-coolable closed-shell atoms (eg. Yb) with open-shell atoms (alkali-metal atoms, Cr, lanthanides). Recently, a new mechanism which drives Feshbach resonances in systems like RbSr and LiYb were found. However, such Feshbach resonances are extremely narrow: predicted widths are very small compared to resonant field values ($\frac{\Delta_{\mathrm{res}}}{B_{\mathrm{res}}} \approx 10^{-5}$), which limits their application. This *dramatically* contrasts with the case discussed here.

We present entirely new mechanism which might be much more promising for formation of paramagnetic, polar molecules. We focus on mixture of ultracold Cr and Yb atoms. These atoms could form a molecules with huge magnetic moment of $6\mu_B$ and dipole moment of 0.1-0.2 D. If both atoms approach each other, anisotropic spin-spin interaction appears in interaction-distorted Cr atom. Such effect can be as large as 0.5 cm^{-1} near R_e (3.4 Å). This is enough to produce the Feshbach resonances at magnetic fields below 150 G, typically as broad as 0.1-1G (for magnetically ground states of Cr atoms, for *any* isotopic mixture of CrYb).

Because of large coupling and small fields at which resonances occur, the ratio $\frac{\Delta_{\mathrm{res}}}{B_{\mathrm{res}}}$ can be even *4 orders of magnitude* larger than in alkali-metal atom – closed-shell atom mixtures.

Vortices in the final-state continuum of a positron-atom ionization collision

V. D. Rodríguez[1,*], F. Navarrete[2], R. Della Picca[2], J. Fiol[2], and R. O. Barrachina[2]

1. Departamento de Física and Instituto de Física de Buenos Aires, FCEyN, Universidad de Buenos Aires, 1428 Buenos Aires Argentina
2. Centro Atómico Bariloche and Instituto Balseiro (Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo), 8400 S. C. de Bariloche, Río Negro, Argentina
**vladimir@df.uba.ar*

We employ a continuum distorted wave (CDW) approximation with the correct kinematics to calculate the probability flux of the final-state continuum in the ionization of atoms by positron impact. Different structures are unveiled and investigated, among them a vortex, akin to a deep minimum recently uncovered in the triple differential cross section for electron-atom ionization collision [1]. We also explore how this structure develops in the multidimensional continuum of the impinging positron, the emitted electron and the recoiling ion. Finally, we discuss this finding in the framework of Madelung's hydrodinamical and de Broglie - Bohm formulations of Quantum Mechanics.

Reference

[1] J. H. Macek, J. B. Sternberg, S. Y. Ovchinnikov and J. S. Briggs, "Theory of Deep Minima in (e,2e) Measurements of Triply Differential Cross Sections", Phys. Rev. Lett. **104**, 033201 (2010).

Threshold resonances in ultracold chemical reactions

Ionel Simbotin[1], Subhas Ghosal[1,2], and Robin Côté[1,*]

1. 2152 Hillside Road, University of Connecticut, Storrs, Connecticut 06962, USA
2. Department of Chemistry, BITS Pilani, Hyderabad Campus, Hyderabad - 700078, India
**rcote@phys.uconn.edu*

We extend our previous work on ultracold reactive scattering of D + H_2 [1] to study the role of resonances on cross sections and rate coefficients, by scaling the mass of the system. We analyze the effects of near threshold resonances on the low energy behavior of cross sections for reactive scattering systems with reaction a barrier (*e.g.* Cl + H_2, D + H_2). We find an anomalous behavior when a resonance pole is very close to the threshold of the entrance channel. For inelasticprocesses, including reactive ones, the anomalous energy dependence of the cross sections is given by $\sigma \sim E^{-3/2}$. However, at vanishingly low energies, the standard Wigner's threshold behavior ($\sigma \sim E^{-1/2}$) is eventually recovered, but limited to a much narrower range of energies. When the cross sections are averaged to obtain rate coefficients, the anomalous behavior persists; indeed, we find an intermediate regime of ultralow temperatures, where the inelastic rate coefficients behave as $K \sim 1 / T$, before recovering the Wigner regime's constant rate.

Reference

[1] I. Simbotin, S. Ghosal, and R. Côté, *A case study in ultracold reactive scattering: D + H_2*, Phys. Chem. Chem. Phys. **13**, pp. 19148-19155 (2011).

Break up of Rydberg superatoms via dipole-dipole interactions

S. Möbius, M. Genkin*, S. Wüster, A. Eisfeld, and J. M. Rost

Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany
**genkin@pks.mpg.de*

We investigate resonant dipole-dipole interactions between two Rydberg-blockaded atom clouds. The Rydberg blockade leads to collective states, sometimes called 'superatoms', in which all atoms within a cloud share a coherent single Rydberg excitation. Recent articles [1-4] have demonstrated the potential of Rydberg aggregates as a medium for quantum transport. Here, we address the possibility to extend single atom sites to sites of Rydberg-blockaded clouds. It is found that in such a setup the dynamics is akin to an ensemble average over systems where just one atom per cloud participates in entangled motion and excitation transfer, and no collective motion of all atoms occurs. The dipole-dipole interaction thus 'breaks up' the superatoms by removing the excitations from the clouds. Collective motion of superatoms, however, becomes possible if additional coupling between ground state atoms is induced via far-detuned laser dressing.

References

[1] S. Wüster *et al.*, Phys. Rev. Lett. **105**, pp. 053004 (2010).
[2] S. Möbius *et al.*, J. Phys. B **44**, pp. 184011 (2011).
[3] S. Westermann *et al.*, Eur. Phys. J. D **40**, pp. 37 (2006).
[4] O. Mülken *et al.*, Phys. Rev. Lett. **99**, pp. 090601 (2007).

Relativistic Rayleigh scattering and photoeffect from K-shell bound electrons

A. Costescu[1,2], S. Spanulescu[1,*], and C. Stoica[2]

1. Hyperion University of Bucharest, Bucharest 030629, Romania
2. University of Bucharest, MG11,Bucharest 76900, Romania
**severspa2004@yahoo.com*

We perform a relativistic analytical calculation of the second-order S-matrix element in the case of the elastic scattering photons from K-shell electrons using the Coulombian Green function method. We used the integral representation of the Green function for Dirac equation with Coulomb field due to Hostler [1], taking into account the main, the first and the second iteration terms as well as the expression of the particular relativistic Coulombian Green function given by Martin and Glauber [2]. Exact Dirac spinors for the bound K-shell electrons are considered for calculating the transition amplitudes. Thus, our analytical formulae for the angular distribution are relativistic exact up to the order $(\alpha Z)^4$ for the real part and $(\alpha Z)^7$ for the imaginary part of the elastic scattering amplitudes. Our method is valid for any values of the photon energy, nuclear charge Z and scattering angle θ, i.e. for any realistic physical case. The relativistic angular distribution is rather simple, involving three Appell functions F_1. The imaginary part of the forward scattering amplitude also gives the photoeffect, pair production (via the optical theorem) and the electron capture (via the detailed balance principle) total cross-sections.

The work of C. Stoica was supported by the grant POSDRU/89/1.5/S/58852 co-financed by ESF.

References

[1] L. Hostler , J. Math. Phys. **5**, 591 (1964).
[2] P. C. Martin and R. J. Glauber, Phys. Rev. **109**, 1307 (1958).

Theory of long-range photoassociation of ultracold atoms with ultracold molecules

Jesús Pérez-Ríos*, Maxence Lepers, and Olivier Dulieu

Laboratoire Aimé Cotton, CNRS, Bât. 505, Orsay, France
**jprios84@gmail.com*

As dense samples of ultracold bi-alkali molecules are available, their association with an excited ultracold atom to create triatomic molecules is now under reach. We present a model for atom-molecule photoassociation (PA) based on the long-range multipolar interactions between the partners, which have been shown quite complex due to the competition between the rotational energy of the molecule and the internal energy of the atom [1, 2]. We first investigate the long-range couplings between the various entrance channels of the process, and their effect on the energy level spectrum of the excited atom-molecule complex. A preliminary estimate for the PA is derived, based on a one-dimensional approach of the collision between the atom and the molecule in a defined rovibrational level. Possible ways to detect the atom-molecule association will be discussed.

References

[1] M. Lepers and O. Dulieu, *Cold Atom-Molecule Photoassociation: long-range interactions beyond $1/R^n$ expansion*, Eur. Phys. J. D **65**, pp. 113-123 (2011).
[2] M. Lepers and O. Dulieu, *Longe-range interaction between ultracold atoms and molecules including atomic spin-orbit*, Phys. Chem. Chem. Phys. **13**, pp. 19106-19113 (2011).

Elastic S-wave scattering of low-energy electrons by metastable helium atoms

Jun-Yi Zhang[1,*], Ying Qian[2], Zong-Chao Yan[3,4], and Udo Schwingenschlögl[1]

1. Division of Physical Science & Engineering, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
2. Supercomputing Laboratory, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
3. Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
4. Department of Physics, University of New Brunswick, Fredericton E3B 5A3, Canada
**Junyi.Zhang@kaust.edu.sa*

Excited atoms, particularly those in metastable states, have large scattering cross sections. Thus, even if a small amount is present in a discharge environment, large scattering cross sections, high dipole polarizabilities, and low excitation and ionization potentials can dramatically affect the behavior of the discharge. In this work, the elastic S-wave quartet scattering of low-energy electrons from metastable helium atoms is studied by the confined variational method [1, 2]. The method exploits the theory that two Hamiltonian operators having the same long-range potential give rise to the same phase shifts for the same energy upon removal of the confining potential. An initial verification is performed on the elastic scattering of electrons by a model potential. Then the stochastic variational method is used to determine the energies of the confined e^-–He(2^3S^e) system and the phase shifts of the elastic scattering are determined with the use of one-dimension potentials.

References

[1] J. Mitroy, J. Y. Zhang and K. Varga, Phys. Rev. Lett. **101**, 123201 (2008).
[2] J. Y. Zhang, J. Mitroy and K. Varga, Phys. Rev. A **78**, 042705 (2008).

Cooling of large molecules for FTMW spectroscopy

David Patterson* and John M. Doyle

Harvard University, Cambridge, MA
**dave@cua.harvard.edu*

Large, gas phase molecules, including benzonitrile, 1-2 propanediol, and fluorene are collisionally cooled in a cell to a temperature of 5 K and detected via Fourier transform microwave spectroscopy (FTMW). Helium buffer gas cools the molecules, which originate from a high flux room temperature beam. We see no evidence of helium-molecule clustering, as expected in this unique, low helium density environment. This method offers comparable spectral resolution to existing seeded pulsed supersonic beam/FTMW spectroscopy experiments but with higher number sensitivity. It is also an attractive tool for quantitative studies of cold molecule-helium and molecule-molecule elastic and inelastic collisions at low energy. Possible adaptions of the technique are presented. These would allow this system to serve as a sensitive broad spectrum mixture analyzer, an enantiomer-specific detector of chiral molecules in a mixture, a high resolution slow-beam microwave spectrometer, and/or a low-velocity, high-flux source for molecule slowing experiments. The 5 Kelvin flourene ($C_{13}H_{10}$) observed here represents the largest cold gas phase molecule observed in a non-moving frame [1, 2].

References

[1] D. Patterson and J. M. Doyle, *Cooling and Collisions of Large Gas Phase Molecules*, P.C.C.P. **12**, pp. 9736-9741 (2010).
[2] M. Beaky, D. Flatin, J. Holton, T. Goyette, and F. C. De Lucia, *Hydrogen and Helium Pressure Broadening of CH_3F Between 1 K and 600 K*, J. Mol. Structure **352-352**, pp. 245-251 (1995).

Toward optical loading of CaH into a magnetic trap

Hsin-I. Lu[1,2,*], Julia Piskorski[2,3], Boerge Hemmerling[2,3], Ivan Kozyryev[2], and John M. Doyle[2,3]

1. School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
2. Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02138, USA
3. Department of Physics, Harvard University, Cambridge, MA 02138, USA
**lu@cua.harvard.edu*

Producing cold, chemical diverse molecules in a large quantity can have a profound impact in various fields, including quantum simulation, cold, controlled chemistry, and precision measurements. Here, we report the progress toward loading a very slow CaH molecular beam into a deep magnetic trap, by employing optical pumping techniques. A cold, slow CaH beam is produced from a two-stage buffer gas cell [1] and has a forward velocity of 65 m/s (longitudinal and transverse velocity spreads are 40 m/s and 50 m/s, respectively). A hexapole magnetic lens is used to focus the molecular beam to the 4T deep magnetic trap, locating at 30 cm from the source. When the molecules reach the trap area, we plan to apply two optical pumping lasers at the saddle point and near the trap center to achieve irreversible loading and magnetic deceleration. A Monte Carlo simulation indicates this loading process can load ≈ 0.1% of the molecules that exit the beam source into the trap. Since only a few photon scattering is needed to achieve loading, this method is applicable to a wide range of magnetic molecules, including those without closed cycling transitions. Continuously loading to build up the molecular density is feasible. We plan to co-load CaH with Li atoms to study cold CaH-Li collisions and investigate the feasibility of sympathetic cooling of CaH [2].

References

[1] H.-I. Lu, J. Rasmussen, M. J. Wright, D. Patterson and J. M. Doyle, *Cold and Slow Molecular Beam*, Phys. Chem. Chem. Phys. **13**, pp.,18986-18990 (2011).
[2] T. V. Tscherbul, J. Kłos, and A. A. Buchachenko, *Ultracold spin-polarized mixtures of $^2\Sigma$ molecules with S-state atoms: Collisional stability and implications for sympathetic cooling*, Phys. Rev. A **84**, 040701(R) (2011).

A permanent magnet trap for buffer gas cooled atoms and molecules

D. M. M. Nohlmans, S. M. Skoff, R. J. Hendricks, N. Bulleid, D. M. Segal, B. E. Sauer, E. A. Hinds, and M. R. Tarbutt

Centre for Cold Matter, Blackett Laboratory, Imperial College London, UK

Cold molecules are set to provide a wealth of new science compared to their atomic counterparts [1], predominantly due to their vastly richer structure as a result of rotational and vibrational energy levels. Here we want to present preliminary results for cooling and trapping molecules in a permanent magnetic trap. By replacing the conventional buffer gas cell [2] with an arrangement of permanent magnets, we will be able to trap a fraction of the molecules right where they are cooled. For this purpose we have designed a quadrupole trap using NdFeB magnets, which has a trap depth of 0.4 K for molecules with a magnetic moment of 1 μ_B. Cold helium gas is pulsed into the trap region by a solenoid valve and the molecules are subsequently ablated into this and cooled via elastic collisions. First we will test the trapping arrangement with lithium atoms as they are easier to make. After having optimised the trapping and detection processes, we will use the same trap for YbF molecules.

References

[1] L. D. Carr, D. DeMille, R. V. Krems, and J. Ye, *New. J. Phys*. **11**, 055049 (2009).
[2] S. M. Skoff, R. J. Hendricks, C. D. J. Sinclair, J. J. Hudson, D. M. Segal, B. E. Sauer, E. A. Hinds and M. R. Tarbutt, *Phys. Rev. A* **83**, 023418 (2011).

Collisions of ultracold molecules - beyond the universal regime

Krzysztof Jachymski[1], Michał Krych[1,*], Zbigniew Idziaszek[1], and Paul S. Julienne[2]

1. Faculty of Physics, University of Warsaw, Hoża 69, 00-681, Warsaw, Poland
2. Joint Quantum Institute, NIST and the University of Maryland,
Gaithersburg, Maryland 20899-8423, USA
**krych@fuw.edu.pl*

Accurate description of quantum degenerate molecular gases, that have been realized experimentally [1,2], constitutes a challenging task from theoretical point of view. Understanding of two body collisions is an essential step towards the full comprehension of such a system. We analyse the problem within the quantum defect theory [3] framework. Our calculations are in agreement both with ultracold s-wave limit [4] and high temperature classical regime. Finite temperature effects are described for the van der Waals interaction. Shape resonances contribution to reactive rates is discussed. We also develop a quantum analytical approximation for moderate and high energies, which predicts quantum corrections even for room temperatures.

References
[1] D. S. Jin and J. Ye, Physics Today **64**, pp. 27-31 (2011).
[2] K. K. Ni, S. Ospelkaus, M. H. G. de Miranda, A. Pe'er, B. Neyenhuis, J. J. Zirbel, S. Kotochigova, P. S. Julienne, D. S. Jin, and J. Ye, Science **322**, pp. 231 (2008).
[3] F. H. Mies, Journ. Chem. Phys. **80**, pp. 2514 (1984).
[4] Z. Idziaszek and P. S. Julienne, Phys. Rev. Lett. **104**, pp. 113202 (2010).

Sisyphus cooling of polyatomic molecules

M. Zeppenfeld*, B. Englert, Rosa Glöckner, A. Prehn, and G. Rempe

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
**martin.zeppenfeld@mpq.mpg.de*

Interest in ultracold polar molecules has experienced tremendous growth in recent years, with potential applications reaching beyond those of ultracold atoms due to additional internal degrees of freedom and long-range dipole-dipole interactions. Developing methods to prepare the required ensembles of ultracold molecules has been a formidable challenge. To this end, we have now achieved first results with opto-electrical cooling [1], a general Sisyphus-type cooling scheme for polar molecules. Molecules are cooled by more than a factor of 4 with an increase in phase space density by a factor of 7. The scheme proceeds in an electric trap, and requires only a single infrared laser with additional RF and microwave fields. The cooling cycle depends on generic properties of polar molecules and can thus be extended to a wide range of molecule species. Ongoing improvements in our trap design will allow cooling to sub-mK temperatures and beyond, opening wide-ranging opportunities for fundamental studies with polyatomic molecules at ultracold temperatures.

Reference
[1] M. Zeppenfeld *et. al.*, *Opto-Electrical Cooling of Polar Molecules*, Phys. Rev. A **80**, 041401 (2009).

Optical trapping wavelengths of bialkali molecules in an optical lattice

Romain Vexiau*, Nadia Bouloufa, Mireille Aymar, and Olivier Dulieu

Laboratoire Aimé Cotton, CNRS, Université Paris-Sud XI, Orsay, France
**romain.vexiau@u-psud.fr*

The present work aims at finding optimal parameters for trapping of bialkali molecules in optical lattices, with the perspective of creating a quantum degenerate gas of ground-state molecules. We have calculated dynamic polarizabilities of bialkali molecules subject to an oscillating electric field, using accurate potential curves and electronic transition dipole moments. We show that for particular wavelengths of the optical lattice, called “magic wavelength”, the polarizability of the ground-state molecule is equal to the one of the Feshbach molecule. As the creation of the sample of ground-state molecules relies on an adiabatic population transfer from weakly-bound molecules created on a Feshbach resonance, such a coincidence ensures that both the initial and final states are favorably trapped by the lattice light, allowing optimal transfer in agreement with experimental observation.

Laser cooling molecules

Valentina Zhelyazkova, Aki Matsushima, Anne Cournol, Jony Hudson, Michael Tarbutt, Ben Sauer, and Ed Hinds

Imperial College London, The Blackett Laboratory, Prince Consort Road, London, SW7 2BW, UK
**valentina.zhelyazkova08@imperial.ac.uk*

Laser cooling is a simple technique routinely used to cool atoms down to temperatures in the mK range. As the presence of a closed transition is essential for the cooling to work, laser cooling is usually not tractable in molecules due to their complex structure. Molecules can rotate and vibrate and usually only scatter a few photons before they end up in a dark state. In particular, the molecule often changes a vibrational state in the absorption-emission cycle. Recently, a whole class of polar molecules (e.g. CaF, SrF, BaF and TiO) has been shown to possess a highly diagonal Franck-Condon matrix, which makes them viable candidates to be laser cooled.

We demonstrate a scheme for laser cooling of a supersonic beam of CaF and SrF radicals. The Franck-Condon factor for the relevant transition makes it possible for the molecules to scatter 10^4 photons with only one or two vibrational repump lasers. We show evidence of longitudinal slowing and cooling in CaF and beam brightening and cooling in SrF.

Spectroscopic investigation of the $A\ ^1\Sigma^+$, $3\ ^1\Sigma^+$, $1\ ^1\Pi$, $2\ ^3\Sigma^+$, and $b\ ^3\Pi$ states of $^{39}K^{85}Rb$ and optimal STIRAP transfer paths

Jin-Tae Kim[1], Yonghoon Lee[2], Bongsoo Kim[3], Dajun Wang[4], Phillip L. Gould[5], Edward E. Eyler[5], and William C. Stwalley[5,*]

1. Dept. of Photonic Engineering, Chosun Univ., Gwangju 501-759, Korea
2. Dept. of Chemistry, Mokpo National Univ., Jeonnam 535-729, Korea
3. Dept. of Chemistry, KAIST, Daejon 305-701, Korea
4. Dept. of Physics, Chinese Univ. of Hong Kong, Shatin, N. T., Hong Kong
5. Dept. of Physics, Univ. of Connecticut, Storrs, CT 06269-3046, USA
**contact for this paper at w.stwalley@uconn.edu*

By combining molecular beam (MB) spectra with two distinct sets of ultracold molecule spectra (UM+ and UM–), we have successfully assigned the mutually perturbing $A\ ^1\Sigma^+$, $3\ ^1\Sigma^+$, $1\ ^1\Pi$, $2\ ^3\Sigma^+$, and $b\ ^3\Pi$ states of ultracold $^{39}K^{85}Rb$ in the region 11,000-12,000 cm^{-1} above the ground state dissociation limit. The UMs are formed by radiative decay following photoassociation to a specific level of the $3(0^+)$ state (UM+) or the $3(0^-)$ state (UM–). For the MB spectra, cold $^{39}K^{85}Rb$ molecules were formed in the $X\,^1\Sigma^+$, $v'' = 0$ ground state. The UM+ and UM– spectra are quite similar, except that the A and $3\ ^1\Sigma^+$ states can occur only in the UM+ spectra. The other three states occur in both the UM+ and UM– spectra. Similar investigations in other energy regions appear promising for characterizing perturbations all the way up to the dissociation limit. We also show that a multiplicative combination of MB and UM spectra, with an offset appropriate to the binding energy of the lower levels, can determine optimal paths for STIRAP, even when spectral assignments are not yet available.

Measurements and calculations of molecule formation by nanosecond-timescale frequency-chirped pulses

J. L. Carini[1], C. E. Rogers III[1], P. L. Gould[1,*], J. A. Pechkis[2], S. Kallush[3], and R. Kosloff[4]

1. Department of Physics, University of Connecticut, Storrs, CT 06269, USA
2. Naval Research Laboratory, 4555 Overlook Avenue S.W., Washington, DC 20375, USA
3. Department of Physics and Optical Engineering, ORT Braude, P.O. Box 78, Karmiel, Israel
4. Department of Physical Chemistry and the Fritz Haber Research Center for Molecular Dynamics, The Hebrew University, 91094, Jerusalem, Israel
**phillip.gould@uconn.edu*

We report on measurements and quantum calculations of $^{87}Rb_2$ formation by pulses of frequency-chirped light on the nanosecond timescale. The experiment starts with cold atoms in a magneto-optical trap and uses frequency-chirped photoassociation near the dissociation limit to produce excited molecules. Some of these molecules spontaneously decay into high vibrational levels of the ground state and are detected by pulsed-laser ionization. Our chirps typically sweep 1 GHz in 100 ns and the pulses are 40 ns wide. The time-dependent photoassociation is modeled by following the dynamics of the collisional wave functions on both ground-state and excited-state potentials in the presence of the chirped light. Because of the relatively long time scales involved, spontaneous emission from the excited state must be accounted for. Dependencies on pulse intensity and chirp direction will be presented. This work is supported by DOE.

Laser cooling of dense gases by collisional redistribution of radiation

Anne Sass[1,*], Ulrich Vogl[2], Peter Moroshkin[1], and Martin Weitz[1]

1. Institut für Angewandte Physik der Universität Bonn, Wegelerstrasse 8, 53115 Bonn
2. Joint Quantum Institute, University of Maryland in College Park, USA
**sass@iap.uni-bonn.de*

We study laser cooling of atomic gases by collisional redistribution of fluorescence, a technique applicable to ultradense atomic ensembles of alkali atoms at a few hundred bar of buffer gas pressure [1, 2, 3]. The cooled gas has a density of more than ten orders of magnitude above the typical values in Doppler cooling experiments of dilute atomic gases. In frequent collisions with noble gas atoms in the dense gas system, the energy levels of the alkali atoms are shifted, and absorption of far red detuned incident radiation becomes feasible. The subsequent spontaneous decay occurs close to the unperturbed resonance frequency, leading to a redistribution of the fluorescence. The emitted photons have a higher energy than the incident ones, and the dense atomic ensemble is cooled. We here report on recent experiments of a Rb-noble gas mixture. For the future, we expect that redistribution laser cooling can also be applied to molecular gas samples.

References

[1] U. Vogl and M. Weitz, Nature **461**, 70 (2009).
[2] A. Sass, U. Vogl, and M. Weitz, Appl. Phys. B **102**, 503 (2011).
[3] U. Vogl, A. Sass, S. Hasselmann, and M. Weitz, J. Mod. Opt. **58**, 1300 (2011).

Antihydrogen production by two stage charge exchange

D. W. Fitzakerley[1], M. C. George[1], E. A. Hessels[1], C. H. Storry[1], M. Weel[1], G. Gabrielse[2], R. Kalra[2], W. S. Kolthammer[2], R. McConnell[2], P. Richerme[2], A. Mullers[3], J. Walz[3], D. Gronzka[4], W. Oelert[4], T. Sefzick[4], and M. Zielinski[4]

1. Department of Physics and Astronomy, York University, Toronto Ontario M3J 1P3, Canada
2. Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
3. Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany
4. IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
**Daniel.william.fitzakerley@cern.ch*

Antihydrogen ($\overline{H}$) atoms are produced via laser-controlled, two-stage charge exchange in a cryogenic Penning trap. $6x10^6$ antiprotons ($\overline{p}$) and 3×10^8 positrons (e^+) are held in a nested well potential structure. Cs* atoms, produced via laser excitation within the cryogenic Penning trap travel, radially across the trap and through the e^+ plasma to produce Ps*. The Ps* atoms are produced isotropically, with some atoms moving along the axis of the Penning trap and interacting with the cold $\overline{p}$ via a second charge exchange to form potentially very cold $\overline{H}$. $\overline{H}$ formation is detected by comparing the $\overline{p}$ annihilation counts with Cs excited to the Rydberg state to those obtained when the Cs remains in the ground state.

Absorption imaging of laser cooled trapped ions

Benjamin G. Norton*, Erik W. Streed, Andreas Jechow, and David Kielpinksi

Centre for Quantum Dynamics, Griffith University, Brisbane, Australia
**benjamin.g.norton@gmail.com*

Absorption imaging has played a key role in the advancement of science from van Leeuwenhoek's discovery of red blood cells to the observation of dust clouds stellar nebula. Here we show the first absorption image of a single atom isolated in vacuum through the absorption of photons resonant with the 370 nm $S_{1/2}$ to $P_{1/2}$ transition in Yb^+ [1]. The optical properties of atoms are well understood making this system ideal for fundamental tests of quantum physics. We have observed image contrasts of 3.1(3)%, the maximum allowed by quantum theory for our system. The imaging resolution was on the order of the illumination wavelength, close to the best image resolution achievable [2]. The image contrast and resolution were far higher than previous work in single molecules [3] in which contrasts of only a few parts per million was obtained. Using this technique we will show work towards a single atom optical modulator which exploits the nonlinear saturation effect of atomic absorption.

References

[1] E. W. Streed, *et al.*, *Absorption imaging of a single atom.*, arXiv:1201.5280v1 [quant-ph], (2012).
[2] A. Jechow, *et al.*, *Wavelength-Scale Imaging of trapped ions using a phase Fresnel lens.*, Optics Letters **36**, pp. 1371-1373 (2011).
[3] M. Celebrano, *et al.*, *Single-molecule imaging by optical absorption.* Nature Photonics **5**, pp. 95-98 (2011).

Laser cooling to quantum degeneracy

Simon Stellmer[1], Benjamin Pasquiou[1], Rudolf Grimm[1,2], and Florian Schreck[1,*]

1. Institute for Quantum Optics and Quantum Information, OEAW, Innsbruck, Austria
2. Institute for Experimental Physics and Research Center for Quantum Physics,
University of Innsbruck, Innsbruck, Austria
**Florian.Schreck@oeaw.ac.at*

We present Bose-Einstein condensation (BEC) of strontium by laser cooling. So far, every cooling method capable of reaching BEC in dilute gases, relied on evaporative cooling as the last, crucial cooling stage. Laser cooling to BEC has been strongly discussed middle of the '90s, but the experimental capabilities of that time were insufficient to reach that goal. Strontium's unique properties, especially its narrow intercombination line, allow us a new approach. Laser cooling using this narrow line is ableto cool strontium atoms to a temperature below 1μK and a phase-space density of ~ 0.1. Further increase of the phase-space density is hindered by reabsorption of photons scattered during laser cooling. We have developed a method with which we can tune the atoms in a small spatial region of a laser cooled sample far out of resonance with the cooling light, overcoming this limitation. To support the sample against gravity, it is held in an optical dipole trap. To increase the density of the gas in the region where it is protected from cooling light, we locally create a deeper dipole potential, into which atoms accumulate by elastic collisions. BECs of 100 thousand atoms are created on a timescale of 100 ms. To demonstrate the cooling power provided by laser cooling, we repeatedly destroy the BEC by locally heating it and observe the formation of a new BEC for more than thirty heating/cooling cycles. It should be possible in a simple way to generalize this new method in order to produce a continuous BEC.

Power scaling of an all-solid-state laser source for trapping lithium

Andrea Bergschneider[1, 2,*], Ulrich Eismann[1], Franz Sievers[1,**], Andrew Grier[1], Frédéric Chevy[1], and Christophe Salomon[1]

1. Laboratoire Kastler Brossel, CNRS UMR 8552, UPMC, Ecole normale supérieure, 24 rue Lhomond, 75231 Paris, France
2. Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Germany
**andrea.bergschneider@mpi-hd.mpg.de, **franzl.sievers@googlemail.com*

We present an all-solid-state laser source emitting up to 2.2 ,W of narrowband 671-nm light, frequency-locked to the lithium D-line transitions for laser cooling applications. It consists of a solid-state Nd:YVO_4 ring laser emitting at 1342 nm, with intra-cavity frequency doubling using periodically-polarized potassium titanyl phosphate (ppKTP).

The key issue for power scaling of the setup presented in [1] is the minimization of detrimental thermal effects in the Nd:YVO_4 by choosing and alternative pump wavelength as well as the crystal doping and length. Optimization of the spatial overlap between the pump beam and the cavity mode resulted in an output power of 2.5 W of the non-doubled laser. We obtain mode-hope-free tuning over more than 6 GHz. Furthermore, we observe self-mode-locking when detuning the phase-matching of the nonlinear crystal by adjusting the temperature of the crystal sufficiently far from the optimal value for doubling.

Reference

[1] U. Eismann *et al.*, *An all-solid-state laser source at 671 nm for cold atom experiments with lithium*, Appl. Phys. B **106**, pp. 25-36 (2012).

Fiber optical tweezers for single atom trapping

Sébastien Garcia, Dominik Maxein, Leander Hohmann, Jakob Reichel, and Romain Long

Laboratoire Kastler Brossel, CNRS/UPMC/ENS, Paris, France
**long@lkb.ens.fr*

Trapping and manipulation of single atoms is one of the key elements in quantum optics and quantum information. To achieve single atom trapping, a well-established technique is to use a tightly confining dipole trap. However, the complexity and the size of the required optics makes integration and scalability quite challenging. Our approach is to simplify and to miniaturize atom tweezers by using a single-mode fiber fixed to a small aspheric lens. This simple pre-aligned system, placed inside a small all-glass vacuum cell, traps the atom in the collisional blockade regime and collects the fluorescence of the atom. We present experimental results on single atoms trapping in our dipole trap, especially photon-antibunching in the fluorescence of single atoms. We chop the dipole light in order to get during the dark phase a free single-atom with no light shift and to avoid the generation of resonant photons by Raman scattering of the trapping light inside the fiber. We discuss current efforts towards using our single atoms as a single photon source with good indistinguishability and towards pursuing miniaturization and integration of our atom tweezers.

Small crystals in Penning traps

Sandeep Mavadia*, Shailen Bharadia, Daniel Crick, Joe Goodwin, Graham Stutter, Daniel Segal, and Richard Thompson

Blackett Laboratory, Imperial College London, London SW7 2AZ, UK
**sandeep.mavadia@imperial.ac.uk*

Ion traps allow controlled coherent interactions with individual particles over long periods and let ions form stable three dimensional crystals at low temperatures. For small numbers of ions the crystals form simple structures such as linear strings [1] and tetrahedral pyramids [2] but for larger numbers, the ions can be made to form regular crystalline structures [3]. Their shape is determined by the trapping frequencies and the magnitude of the magnetic field used. We image different crystal configurations for small numbers of ions in a Penning trap and have made progress towards resolved sideband spectroscopy. The large magnetic field used in the trapping poses some challenges; we use a high frequency modulator to simplify the laser cooling in the presence large Zeeman splitting.

References
[1] D. R. Crick, H. Ohadi, I. Bhatti, R. C. Thompson, and D. M. Segal "Two-ion Coulomb crystals of Ca^+ in a Penning trap", Optics Express **16**, 2351 – 2362, (2008).
[2] R. C. Thompson and D. C. Wilson "The motion of small numbers of ions in a Penning trap", Z Phys D Atom Mol Cl **42**, 271 – 277, (1997).
[3] T. B. Mitchell, J. J. Bollinger, X.-P. Huang, W. M. Itano, and D. H. E. Dubin "Direct observations of the structural phases of crystallized ion plasmas", Phys. Plasmas **6**, 1751 – 1758, (1999).

Large single layer ion Coulomb crystals in a printed circuit board surface trap

B. Szymanski*, B. Dubost, R. Dubessy, S. Guibal, J.-P. Likforman, and L. Guidoni

Université Paris–Diderot, Sorbonne Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques, UMR 7162 CNRS, F-75205 Paris, France
**benjamin.szymanski@univ-paris-diderot.fr*

We designed and operated a surface ion trap, with an ion-substrate distance of 500 μm, realized with standard printed-circuit-board techniques. The trap has been loaded with up to a few thousand Sr^+ ions in a three dimensional Coulomb-crystal regime. The analytical model of the pseudo-potential allowed us to determine the parameters that drive the trap into anisotropic regimes in which we obtain large ($N > 150$) purely two dimensional (2D) ion Coulomb crystals lying parallel to the surface of the substrate. Smaller single-layer crystal oriented in a plane orthogonal to the substrate have also been obtained. In both cases micromotion compensation along the three spatial directions improved crystal stability. The single layer character of these Coulomb crystals has been checked by using two independent imaging systems aligned along orthogonal directions. These crystals may open a simple and reliable way to experiments on quantum simulations of large 2D systems [1, 2].

References
[1] D. Porras, and J. I. Cirac, *Quantum Manipulation of Trapped Ions in Two Dimensional Coulomb Crystals*, Phys. Rev. Lett. **96**, 250501 (2006).
[2] B. Szymanski, R. Dubessy, B. Dubost, S. Guibal, J.-P. Likforman, and L. Guidoni, *Large two dimensional Coulomb crystals in a radio frequency surface ion trap*, Appl. Phys. Lett., in press (2012).

Coherent manipulation of atomic velocities by atom interferometry

Alex Dunning[1], Rachel Gregory[1], James Bateman[2], and Tim Freegarde[1,*]

1. School of Physics & Astronomy, University of Southampton, SO17 1BJ, UK
2. Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK
**timf@soton.ac.uk*

We are exploring a variety of schemes for the all-optical cooling and manipulation of clouds of atoms, using arbitrarily-synthesized laser sidebands to drive stimulated Raman transitions between the ground hyperfine states of ^{85}Rb. By combining velocity-selective atom interferometry [1] with the multi-photon impulses achievable with trains of population-inverting π-pulses [2, 3], and using composite error-correction pulses borrowed from NMR [5, 6], our experimental studies aim to demonstrate cooling processes that impart impulses of many $\hbar k$ between spontaneous events and are therefore both faster and less dependent upon spontaneous emission than conventional methods [4], rendering them suitable for species that are currently inaccessible because they lack a sufficiently closed optical transition.

References

[1] M. Weitz and T. W. Hänsch, Europhys. Lett. **49**, pp. 302–308 (2000).
[2] G. Demeter, G. P. Djotyan and J. S. Bakos, J. Opt. Soc. Am. B **15**, pp. 16–24 (1998).
[3] T. Freegarde, G. Daniell and D. Segal, Phys. Rev. A **73**, p. 033409 (2006).
[4] T. Freegarde and D. Segal, Phys. Rev. Lett. **91**, p. 037904 (2003).
[5] J. A. Jones, arXiv eprint 1203.3305v1 (2012).
[6] W. Rakreungdet *et al.*, Phys. Rev. A **79**, p. 022316 (2009).

Lithium as a refrigerant for polar molecules

A. Kaushik*, S. K. Tokunaga, R. J. Hendricks, E. A. Hinds, and M. R. Tarbutt

Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK
**aisha.kaushik05@imperial.ac.uk*

Gases of ultracold polar molecules offer exciting new possibilities in many areas, including precision measurements [1], simulations of many-body quantum systems [2], and quantum information processing [3]. We aim to cool polar molecules by sympathetic cooling with ultracold atoms inside a suitable trap [4]. This poster presents our work on the production and transportation of a dense ultracold cloud of lithium for use as a refrigerant in sympathetic cooling. Upto 10^{10} lithium atoms are loaded from a Zeeman slower into a magneto-optical trap. Using a moving magnetic trap the atoms are transported to a separate chamber where they will later be co-trapped with molecules. We present the design of our setup and our recent results on transport. We also explore the possibility of electrically polarizing the lithium so that dipole-dipole interactions become important in the gas.

References

[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt and E. A. Hinds, Nature **473**, pp. 493-496 (2011).
[2] A. Micheli, G. K. Brennen, and P. Zoller, Nature Physics **2**, pp. 341-347 (2006).
[3] D. DeMille, Phys. Rev. Lett. **88**, pp. 067901 (2002).
[4] S. K. Tokunaga, W. Skomorowski, P. S. Żuchowski, R. Moszynski, J. M. Hutson, E. A. Hinds and M. R. Tarbutt, Eur. Phys. J. D **65**, pp. 141-149 (2011).

On the behaviour of the MOT parameters

Sara Blunk Massardo[1] and André Luiz de Oliveira[2,3,*]

1. Departamento de Física, Universidade Federal do Paraná, Curitiba, PR, Brazil
2. Departamento de Física, Universidade do Estado de Santa Catarina, Joinville, SC, Brazil
3. Instituto Nacional de Óptica e Fotônica, INOF/CNPq, Brazil
**andre.oliveira@udesc.br*

The knowledge of parameters in a magneto-optical trap is very important for doing improvements in a MOT which could be used in very amount of applications like spectroscopy of atoms in ultra-high resolution, atomic clocks and the study of Bose-Einstein condensate [1]. It also contributes to the study on highly excited state atoms. We have revisited some of these parameters in a MOT like the spring constant, capture and escape velocity [2], and simulate the behaviour of all of these parameters under the influence of an oscillating magnetic field. We also perform our study by varying the phase angle in the oscillating magnetic field as a function of detuning, intensity of the trap laser and the magnetic field gradient as well.

References

[1] S. Bize, et. al J. of Phys. B **38**, 449(2005); M. H. Anderson et. al., Science **269**, 198 (1995).
[2] M. R. Loos, S. B. Massardo, R. A. D. S. Zanon and A. L. de Oliveira, Phys. Rev. A, **72**, 25403, (2005).

Preparation of individually trapped atoms using light assisted collisions

A. V. Carpentier, Y. H. Fung, P. Sompet, and M. F. Andersen*

Jack Dodd Center for Quantum Technology, Department of Physics,
University of Otago, New Zealand
**mikkel@physics.otago.ac.nz*

We have used light assisted collisions to prepare an individual neutral atom in a red detuned optical microtrap. When using blue detuned assisted collisions we load single ^{85}Rb atoms with a maximum efficiency of 91% [1]. We design a process in which atoms are lost one by one by transferring energy through inelastic collisions and, at the same time, removing the excess of energy by laser cooling. The process ends when only one atom remains in the trap. We have studied how the final loading efficiency depends on the beams parameters. The maximum loading efficiency is obtained using a collision beam blue detuned by the trap depth over h from the $D1$ $F = 2$ to $F' = 3$ transition. We are able to complete the process within a total preparation time of 542 ms. When red detuned light assisted collisions are used the process will be dominated by pair losses, thus increasing the probability of loading zero atoms. Under this situation we are still able to load single atoms with an efficiency of over 60%.

Reference

[1] A. V. Carpentier, Y. H. Fung, P. Sompet, A. Hilliard, T. G. Walker, and M. F. Andersen, *High efficiency preparation of individually trapped atoms using blue detuned light assisted collisions*, To be submitted.

Rapid slowing of atoms and molecules using optical bichromatic forces

E. E. Eyler[1,*] and M. A. Chieda[1,2]

1. Physics Dept., Univ. of Connecticut, Storrs, CT 06269, USA
2. present address: ASML Corp., Wilton, CT 06897, USA
**eyler@phys.uconn.edu*

The optical bichromatic force (BCF) relies on coherent momentum cycling to produce extremely large decelerations [1]. We demonstrate a prototype BCF slower for an atomic beam of metastable helium that can slow atoms by $\Delta v > 350$ m/s injust a few cm, using only low-cost diode lasers. With minor improvements it is projected to slow atoms to MOT loading velocities. The key is to utilize a modest detuning of 100-200 MHz together with computer-controlled frequency chirping. We show thatfor He*, the usable range of detunings for fixed-frequency BCF is limited to $\lesssim$ 400 MHz.

We also consider the application of BCF slowing to molecules, for which the BCF could serve as a very useful "force multiplier" that allows many stimulated cycles during each radiative lifetime. We show that for the near-cycling $A \leftrightarrow X$ and $B \leftrightarrow X$ transitions in CaF, slowing by $\Delta v = 150$ m/s should be attainable with only a single repumping laser [2]. Experimental tests are underway, with NSF support.

References

[1] M. Cashen and H. Metcalf, *Optical forces on atoms in nonmonochromatic light*, JOSA B **20**, 915 (2003).
[2] M. A. Chieda and E. E. Eyler, *Prospects for rapid deceleration of small molecules by optical bichromatic forces*, Phys. Rev. A **84**, 063401 (2011).

Cooling and trapping… Th-190

Highly charged ions in an electrostatic ion beam trap

Csilla I. Szabo[1,*], Alexandre Vallette[1,2], Laurent Hilico[1] and Paul Indelicato[1]

1. Laboratoire Kastler Brossel, École Normale Supérieure, CNRS, Université P. et M. Curie Paris 6, Paris, France
2. Current address: Bordeaux, France
**szabo@spectro.jussieu.fr*

The study of the dynamics of the ions inside an Electrostatic Ion Beam Trap (EIBT) [1] shows that the stability of the trapping is ruled by a Hill's equation. This result suggests that an EIBT can be analogous with a quadrupolar trap. We show how to plot stability diagrams for the EIBT, which is similar to the Ince-Strutt diagram of quadrupolar traps. The parallelism between these two kinds of traps is illustrated by comparing experimental and theoretical stability diagrams of the EIBT. The main difference with quadrupole traps is that the stability depends only on the ratio of the acceleration and trapping electrostatic potentials, and not on the mass or the charge of the ions. All kind of ions can be trapped simultaneously and since parametric resonances are proportional to the square root of the charge/mass ratio, the EIBT can be used as a mass spectrometer of an infinite mass range. Experimental data obtained with various ions show good agreement with the theory. We also present experimental observation of both parametric and high-order motional resonances, predicted by the model. We currently study how to combine such a trap with a Paul trap to decelerate and store ion beams with a kinetic energy of a few keV.

Reference

[1] D. Zajfman, O. Heber, L. Vejby-Christensen, *et al.*, Phys. Rev. A 55, R1577 (1997).

Atom trap using Casimir interactions

Kanupriya Sinha[1], Darrick E. Chang[2], Jacob M. Taylor, and Bei-Lok Hu[1]

1. Joint Quantum Institute (JQI), University of Maryland, College Park, USA
2. Institut de Ciències Fotòniques (ICFO), Barcelona, Spain
**kanu@umd.edu*

Trapping and guiding atoms close to surfaces is an open challenge that can potentially lead to miniaturized atom-chip devices and strong atom-photon coupling, among its many other applications. The current techniques are limited by background scattering and weak trapping potentials that can be easily overcome by surface forces at short distances. Here, we propose a new scheme that leverages the strength of surface forces to make an atom trap in the presence of an external drive. To achieve this, we take a two level atom out of equilibrium by weakly driving it to the excited state close to a half-dielectric space with Drude-Lorentz model for permittivity. The material resonance and loss are such that the excited state of the atom interacting with the vacuum EM field modes sees a large repulsive potential in the presence of a Rayleigh scattered drive, while the ground state has an attractive $1/r^3$ potential leading to a position dependent detuning of the drive as a function of the atom-surface distance. We show that dressing the atom in presence of a position dependent detuning gives a trap potential close to where the atom is resonantly excited which goes as the Rabi frequency of the laser.

Reference

[1] Buhmann *et al.*, *Casimir-Polder Forces: A nonperturbative approach*, Phys. Rev. A **70**, 052117 (2004).

Hartree self-energy in unitary Fermi gases

Jami J. Kinnunen

Department of Applied Physics, Aalto University School of Science and Technology, Finland
jami.kinnunen@aalto.fi

The Hartree energy shift is calculated for a unitary Fermi gas [1]. By including the momentum dependence of the scattering amplitude explicitly, the Hartree energy shift remains finite even at unitarity. Extending the theory also for spin-imbalanced systems allows calculation of polaron properties. The results are in good agreement with more involved theories and experiments.

Reference

[1] J. J. Kinnunen, *Hartree shift in unitary Fermi gases*, Phys. Rev. A **85**, 012701 (2012).

Crossover trimers connecting continuous and discrete scaling regimes

Shimpei Endo[1,*], Pascal Naidon[2], and Masahito Ueda[1]

1. Department of Physics, University of Tokyo, Japan
2. RIKEN, Nishina Center, Japan
**endo@cat.phys.s.u-tokyo.ac.jp*

For a system of two identical fermions and one distinguishable particle interacting via a short-range potential with a large s-wave scattering length, the Efimov trimers [1] and universal trimers [2] exist in different regimes of the mass ratio [1-3]. The Efimov trimers exhibit a discrete scaling invariance, while the universal trimers feature a continuous scaling invariance. We point out that a third type of trimers, "crossover trimers", exist universally regardless of short-range details of the potential [4]. These crossover trimers have neither the discrete nor continuous scaling invariance. We show that the crossover trimers continuously connect the discrete and continuous scaling regimes as the mass ratio and the scattering length are varied. We identify the regions for the Kartavtsev-Malykh trimers, Efimov trimers, crossover trimers, and non-universal trimers as a function of the mass ratio and the s-wave scattering length by investigating the scaling property and model-independence of the trimers.

References

[1] V. Efimov, Nucl. Phys. A210, 157 (1973).
[2] O. I. Kartavtsev, and A, V. Malykh, J. Phys. B 40, 1429 (2007).
[3] Shimpei Endo, Pascal Naidon, and Masahito Ueda, Few-body systems 51, 207 (2011).
[4] Shimpei Endo, Pascal Naidon, and Masahito Ueda, arXiv:1203.4050v1.

Interaction enhanced imaging of individual Rydberg atoms in dense gases

Georg Günter*, Martin Robert-de-Saint-Vincent, Hanna Schempp,
Christoph S. Hofmann, Shannon Whitlock, and Matthias Weidemüller

Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany
**georg.guenter@physi.uni-heidelberg.de*

We propose a new all-optical method to image individual Rydberg atoms embedded within dense gases of ground state atoms [1]. The scheme exploits interaction-induced shifts on highly polarizable excited states of probe atoms, which can be spatially resolved via an electromagnetically induced transparency resonance. Using a realistic model, we show that it is possible to image individual Rydberg atoms with enhanced sensitivity and high resolution despite photon-shot noise and atomic density fluctuations. In particular we demonstrate the potential of the imaging method to study blockade effects and correlations in the distribution of Rydberg atoms optically excited from a dense gas, applicable in current experiments. Furthermore this new imaging scheme could be extended to other impurities such as ions, and is ideally suited to equilibrium and dynamical studies of complex many-body phenomena involving strongly interacting particles.

Reference

[1] G. Günter *et al.*, *Interaction Enhanced Imaging of Individual Rydberg Atoms in Dense Gases*, Phys. Rev. Lett. **108**, 013002 (2012).

Efimov physics in a many-body background

Nikolaj Thomas Zinner

Department of Physics and Astronomy, Aarhus University, Denmark
zinner@phys.au.dk

The famous prediction of Efimov [1] that an infinitude of three-body bound states appear in short-range interacting three-dimensional systems when there is a two-body bound state at zero energy has generated a large amount of interest in the cold atomic gas community after its initial observation in ^{133}Cs [2]. The theoretical description of these experiments have thus far used the vacuum formalism. However, current experiments are in a regime where the background energy scale (such as the Fermi energy in degenerate Fermi systems) can play a significant role. We demonstrate that while Efimov states can be strongly perturbed by the background, the original scaling ideas play a crucial role for the manner in which the states change. In fact, we find that a many-body scaling law emerges that can be probed in current experiments [3].

References

[1] Efimov, V. *Weakly bound states of three resonantly interacting particles*. Yad. Fiz. **12**, 1080-1091 (1970); *Sov. J. Nucl. Phys.* **12**, 589-595 (1971).
[2] T. Kraemer *et al.*, *Evidence for Efimov quantum states in an ultracold gas of caesium atoms*, Nature **440**, pp. 315-318 (2006).
[3] N. G. Nygaard and N. T. Zinner, *The Fate of the Efimov Effect in a Many-Body World*, arXiv:1110.5854.

Two interacting fermions in a 1D harmonic trap: matching the Bethe ansatz and variational approaches

D. Rubeni[1,*], A. Foerster[1], and I. Roditi[2]

1. Instituto de Física - UFRGS, Porto Alegre, RS - Brazil
2. Centro Brasileiro de Pesquisas Físicas - CBPF, Rio de Janeiro, RJ - Brazil
**diefflima@gmail.com*

In this work, combining the Bethe ansatz approach with the variational principle, we calculate the ground state energy of the relative motion of a system of two fermions with spin up and down interacting via a delta-function potential in a 1D harmonic trap. Our results show good agreement with the analytical solution of the problem, and provide a starting point for the investigation of more complex few-body systems where no exact theoretical solution is available.

Toward a general-excitation-rank relativistic coupled cluster for electronically excited states of atoms and molecules

Mickaël Hubert and Timo Fleig

Laboratoire de Chimie et Physique Quantiques, IRSAMC, Université Paul Sabatier, Toulouse, France

Coupled Cluster (CC) response theory is an established means of calculating electronically excited states of atoms and molecules. Recently, some of us have presented a new Relativistic General Active Space CC method of general order in a 4-component spinor-based framework. We here present the initial implementation of the CC Jacobian for obtaining excited-states energies based on e.g., relativistic CCSD, CC(4_2), CCSDT, CC(4_3), CCSDTQ, etc. up to FCC wavefunctions. We furthermore present an initial application to the Silicon atom and some homologues of the pnictogene hydride AsH, SbH and BiH. It is demonstrated that with the new method the experimental excitation energy from the $\Omega = 0$ ground state to the $\Omega = 1$ first excited state can be approached in a controlled and systematic manner [1]. As an initial step towards the efficient calculation of excited states based on general-order LRCC, we here present a progress report on the implementation of a commutator-based CC Jacobian.

Reference

[1] M. Hubert, L. K. Sørensen, J. Olsen, and T. Fleig, , Phys. Rev. A, accepted (2012).

Dynamics of a multi-line magneto-optical oscillator

James Higbie

Bucknell University, Lewisburg, PA, USA
jmh063@bucknell.edu

The incorporation of a magneto-optical resonance as a magnetically tunable, frequency-selective element in an electronic oscillator is a frequently employed technique in atomic magnetometry. At geomagnetic-scale fields, however, the nonlinear Zeeman effect can cause shifting and splitting of this frequency, resulting in systematic errors. Here, we present theoretical and experimental progress toward an understanding of the dynamics and stability of such a resolved multi-line system in an anti-relaxation-coated ^{87}Rb vapor cell.

Nonzero magnetic field level-crossing spectroscopy in atomic rubidium

M. Auzinsh, A. Berzins, R. Ferber, F. Gahbauer, L. Kalvans, A. Mozers*, and A. Spiss

Laser Centre, University of Latvia, LV-1586 Riga
**art.mozers@gmail.com*

We present experimentally measured level-crossing signals for the hyperfine transitions of the D_2 line of rubidium and show that these signals can be described very precisely by a theoretical model which is based on optical Bloch equations. In our experimental configuration the magnetic field is perpendicular to the electric field vector of the linearly polarized laser radiation. Resonances are observed at the crossing points of the excited state magnetic sublevels with $\Delta m=2$, where m is the magnetic quantum number associated with the excited state total angular momentum F. In contrast to previous studies [1], precise agreement with theory and experiment are now possible because the theoretical model has been improved to include the hyperfine structure of the atomic levels, strong magnetic sublevel mixing in an external magnetic field, and the Doppler effect. The experimental setup has been improved. Measured signals and results from calculations are presented for different values of the laser power density and frequency.

Reference

[1] J. Alnis *et al.*, "The Hanle effect and level crossing spectroscopy in Rb vapour under strong laser excitation" J. Phys. B: At. Mol. Opt. Phys., 36, pp.1161–1173 (2003).

Frequency translation of orbital angular momentum in four-wave mixing

Graeme Walker[1], Aidan S. Arnold[2], and Sonja Franke-Arnold[1]

1. School of Physics and Astronomy, SUPA, University of Glasgow, Glasgow G12 8QQ, UK
2. Dept. of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK

Optical information can be inscribed in the spatial intensity and phase profile of a light mode. Here we report the transfer of phase structure from near-infrared pump light to coherent blue light in a four-wave-mixing process in a rubidium vapour. Coherent light at 420 nm can be generated with high efficiency as part of a cascade when pumping ^{85}Rb with 780 nm and 776 nm pump lasers at two-photon resonance while minimising Kerr lensing [1]. Using shaped pump beam profiles, we observe the transfer of up to 10 units of orbital angular momentum to the generated blue light [2]. We illustrate the quantum nature of the phase profile by pumping with more complicated light profiles, when we observe output modes that are generated due to the interference between the different spatial excitation amplitudes. These results have implications on the inscription and storage of phase information in atomic gases.

References

[1] A. Vernier, S. Franke-Arnold, E. Riis, and A. S. Arnold, *Enhanced frequency up-conversion in Rb vapor*, Opt. Express. **18**, 17020 (2010) and references therein.
[2] G. Walker, A. S. Arnold and S. Franke-Arnold, *Frequency translation of orbital angular momentum in four-wave mixing*, arXiv:1203.1520.

Complete population transfer in a three-state quantum system by a train of pairs of coincident pulses

Andon A. Rangelov* and Nikolay V. Vitanov

Department of Physics, Sofia University, James Bourchier 5 blvd., 1164 Sofia, Bulgaria
**rangelov@phys.uni-sofia.bg*

A technique for complete population transfer between the two end states $|1\rangle$ and $|3\rangle$ of a three-state quantum system with a train of N pairs of resonant and coincident pump and Stokes pulses is introduced [1]. A simple analytic formula is derived for the ratios of the pulse amplitudes in each pair for which the maximum transient population $P_2(t)$ of the middle state $|2\rangle$ is minimized, $P_2^{\max} = \sin^2(\pi/4N)$. It is remarkable that, even though the pulses are on exact resonance, $P_2(t)$ is damped to negligibly small values even for a small number of pulse pairs. The population dynamics resembles generalized π-pulses for small N and stimulated Raman adiabatic passage for large N and therefore this technique can be viewed as a bridge between these well-known techniques.

Reference

[1] A. A. Rangelov and N. V. Vitanov, *Complete population transfer in a three-state quantum system by a train of pairs of coincident pulses*, Phys. Rev. A **85**, 043407 (2012).

Scattering of dilute cold atomic clouds by structured beams

S. Bernon[1], H. Hattermann[1], J. Fortágh[1],
C. L. Hernández-Cedillo[2], and R. Jáuregui[2,*]

1. Physikalisches Institut der Universität Tübingen
Auf der Morgenstelle 14, D-72076 Tübingen, Germany
2. Instituto de Física, Universidad Nacional Autónoma de México
Apdo Postal 20-364, Mexico 01000, Mexico
**rocio@fisica.unam.mx*

We report experimental and theoretical results for the scattering effects on free falling dilute atomic clouds that traverse a microscopically structured laser beam with parabolic symmetry. The dynamics of the phase space distribution is studied. As proposed in Ref. [1], the atomic clouds were observed to split into two or more clouds with a well defined distribution of momenta. It is shown that the product of the angular momentum along the axis of main propagation of the laser beam with the linear momentum along one of the directions perpendicular to that axis is directly transmitted from the light beam to the atomic cloud.

Reference

[1] B. M. Rodríguez-Lara and R. Jáuregui, *Phys. Rev. A* **80**, 011813(R) (2009).

Direct measurement of the rubidium $5P_{3/2}$ excited state diffusion coefficient in helium using degenerate four-wave mixing

Alina Gearba[1,*], Brad Crochet[1], and Randy Knize[2]

1. Department of Physics and Astronomy, University of Southern Mississippi, Hattiesburg, MS, USA
2. Laser and Optics Research Center, US Air Force Academy, Colorado Springs, CO, USA
**alina.gearba@usm.edu*

Measurements of diffusion coefficients for excited state atoms can be difficult since the distances traveled prior to decay are relatively short. However, a new method for measuring excited state diffusion coefficients for alkali atoms in inert buffer gases using degenerate four-wave mixing technique has been demonstrated [1]. It has been shown experimentally that the angular response of the degenerate four-wave mixing signal results in the direct determination of the excited state diffusion coefficient independent of the ground state diffusion coefficient [2]. We have measured the diffusion coefficient for the $5P_{3/2}$ excited state of rubidium in the presence of helium buffer gas at various pressures. Our first experimental results will be presented at the meeting.

References
[1]. D. S. Glassner and R. J. Knize, "Measurement of the Potassium 4P Excited State Diffusion Coefficient in Xenon Gas Using Degenerate Four-Wave Mixing", Phys. Rev. Lett. **74**, pp. 2212-2215 (1995).
[2]. D. S. Glassner, B. Ai and R. J. Knize, "Direct Measurement of Diffusion Coefficients of Cesium $6P_{3/2}$ and $6P_{1/2}$ Excited-State Atoms in Neon Gas", Phys. Rev. A **54**, pp. 3335-3337 (1996).

Observation of high-L state in ultracold cesium Rydberg atoms

J. M. Zhao[1], H. Zhang[1], P. Cheinet[2], S. T. Jia[1], D. Comparat[2], and P. Pillet[2]

1. State Key Laboratory of Quantum Optics and Quantum Optics Devices, Laser Spectroscopy Laboratory, Shanxi University, Taiyuan, 030006, China
2. Laboratoire Aimé Cotton, CNRS/Université Paris-Sud, Orsay, France
**zhaojm@sxu.edu.cn*

The Rydberg states are extremely sensitive to electric field, due to their large polarizability, scaling as n^7. The electric field can be used to precisely tune energy levels and further the interaction strength between Rydberg atoms.

We will present the first experimental observation of the external electric field pulse induced l-mixing and transformation of high-l state (product state) after the excitation of 49S Rydberg states in cesium magneto-optical trap. The measured product state signal strongly depends on the amplitude and duration of external electric field. Here, we suppose that the product state signal mainly comes from the l-mixing and avoided crossing between initially excited nS state and (n-4) manifolds. When an external electric field switches on with rising time of ~10 ns after preparing nS state, nS atoms will nonadiabaticly transit to the product state through avoided crossing points. Furthermore, by applying two identical electric pulses we obtain the oscillation behavior of population between 49S and product states, which can be tuned through altering the widths of two pulses. The mothed can be implemented to control the population of different states.

Motion of an atomic trapped superfluid under oscillatory excitation

P. E. S. Tavares*, G. D. Telles, R. F. Shiozaki, K. M. F. Magalhães, and V. S. Bagnato

Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil
**pedro.ernesto.tavares@usp.br*

We investigate the effects caused by an external oscillatory excitation in a Bose-Einstein condensate of ^{87}Rb atoms at finite temperature. Besides the excitations of collective modes, we observe a relative motion between the condensate component (superfluid) and the thermal component (normal fluid). This relative motion can be view as a counterflow of these two mutually penetrating components, which generates fluctuations on the superfluid. The level of such fluctuations is larger at the points of higher relative velocity. We analyze the system in terms of superfluid Reynolds number and correlate its value with of vortex formation. The presence of counterflow in an oscillatory BEC creates new exciting experimental possibilities and provides explanations of recent performed experiments on quantum turbulence by oscillatory excitation [1].

Reference

[1] E. A. L. Henn, J. A. Seman, G. Roati, K. M. F. Magalhães, and V. S. Bagnato, *Emergence of Turbulence in an Oscillating Bose-Einstein Condensate*, Phys. Rev. Letters **103**, 045301 (2009).

Magneto-optical resonances with polarization modulated light

Evelina Breschi* and Antoine Weis

Physics Department, University of Fribourg
Chemin du Musée 3, CH-1700 Fribourg, Switzerland
**evelina.breschi@unifr.ch*

Magneto-optical resonances have been largely studied during the last century being an excellent method to investigate the properties of atoms and molecules, light beams and them interactions. We report on magneto-optical spectroscopy using resonant polarization modulation of the light beams that is resonant with Zeeman and/or hyperfine transition in cesium atoms. This technique has been used to increase the constrast of the hyperfine clock resonance [1] and to eliminate dead-zones and heading errors in alkali vapor magnetometers by simultaneous excitation of Δm = 1 and 2 Zeeman coherence [2]. The final aim of our project is the development of a sensitive atomic magnetometer with an intrinsic frequency reference.

We thank our colleagues, the mechanics and the electronics pool of the Physics Department. This project is supported by SNF-Ambizione (grant PZ00P2_131926) and by the Pool de Recherche (UniFr).

References

[1] Y.-Y. Jau, E. Miron, A. B. Post, N. N. Kuzma, and W. Happer *Push-pull optical pumping of pure superposition states*, Phys. Rev. Lett. **16**, pp. 160802 (2004).
[2] A. Ben-Kish, and M. V. Romalis *Dead-zone-free atomic magnetometry with simultaneous excitation of orientation and alignment resonances*, Phys. Rev. Lett. **105**, pp. 193601 (2010).

Application of atomic magnetometry to hydrocarbon analysis

Paul Ganssle[1,2,*], Hyun Doug Shin[1,2], Scott Seltzer[1,2], Vikram Bajaj[1,2], Dmitry Budker[3], Svenja Knappe[4], John Kitching[4], and Alexander Pines[1,2]

1. Department of Chemistry, University of California, Berkeley, Berkeley, CA 94720, USA
2. Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
3. Department of Physics, University of California, Berkeley, Berkeley, CA 94720, USA
4. Time and Frequency Division, National Institute of Standards and Technology, Boulder, CA 80305, USA
**pganssle@berkeley.edu*

Alkali metal atomic magnetometers are among the most sensitive magnetic field sensors, operating by optically monitoring the precession of polarized alkali spins. Magnetometer sensitivity is independent of measurement frequency, enabling them to take advantage of Earth's highly homogeneous ambient magnetic field for NMR detection. Unlike SQUID-based sensors, atomic magnetometers require no cryogens, so they can be embedded into portable sensor arrays, such as those used in oil well logging operations. In this work, we use an atomic magnetometer for compositional analysis of water/hydrocarbon mixtures. By making NMR measurements of proton relaxation and diffusion properties of pure and mixed samples, we have demonstrated for the first time that optical magnetometry has sufficient contrast to measure hydrocarbon content in aqueous systems at 0.5 G (Earth's field), with potential applications in petrochemical analysis and oil well logging.

Reference

[1] D. Budker and M. V. Romalis, *Nature Physics* **3**, 227 (2007).

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

A reversible optical to microwave quantum interface

David Vitali[1,*], Shabir Barzanjeh[2], Mehdi Abdi[2], Gerard. J. Milburn[4], and Paolo Tombesi[1]

1. School of Science and Technology, Physics Division, University of Camerino, Camerino (MC), Italy
2. Department of Physics, Faculty of Science, University of Isfahan, Hezar Jerib, 81746-73441, Isfahan, Iran
3. Department of Physics, Sharif University of Technology, Tehran, Iran
4. Centre for Engineered Quantum Systems, The University of Queensland, Saint Lucia, QLD 4072, Australia
**david.vitali@unicam.it*

We describe a reversible quantum interface between an optical and a microwave field using a hybrid device based on their common interaction with a nano-mechanical resonator in a superconducting circuit. We show that, by employing state-of-the-art opto-electro-mechanical devices, one realizes an effective source of (bright) two-mode squeezing with an optical idler (signal) and a microwave signal, which can be used for high-fidelity transfer of quantum states between optical and microwave fields by means ofcontinuous variable teleportation.

Reference

[1] S. Barzanjeh, M. Abdi, G. J. Milburn, P. Tombesi, and D. Vitali, *A reversible optical to microwave quantum interface*, arXiv:1110.6215v1 [quant-ph].

Symmetry aspects of trapped molecules in diamond

Jeronimo R. Maze[1,*], Adam Gali[2], Victor Waselowski[1], Emre Togan[3], Yiwen Chu[3], Alexei Trifonov[3], Efthimios Kaxiras[3], and Mikhail D. Lukin[3]

1. Department of Physics, Pontificia Universidad Católica, Santiago, Chile
2. Research Institute for Solid State Physics and Optics, Hungarian Academy of Sciences, Budapest, Hungary
3. Department of Physics, Harvard University, Cambridge, USA
**jmaze@uc.cl*

Color centers can be considered as trapped molecules in solids and they have emerged as promising candidates for many applications involving the access and manipulation of quantum degrees of freedom. Applications such as high precision magnetic field measurements, quantum information and communication, and single photon sources require a detailed understanding of the electronic properties of defects in solids. Here we will discuss how the symmetry of the crystal field affects the dynamics of color centersvia their selection rules, and spin-spin and spin-orbit interactions. In particular we will discuss the implications of the crystal field on spin-preserving optical transitions of the nitrogen-vacancy defect [1] and other centers, and their response to external perturbations such as radiation, electric and magnetic fields. The crystal field symmetry imposes advantages and limitations for the successful implementation of the above mentioned applications.

Reference

[1] J. R. Maze, A. Gali, E. Togan, Y. Chu, A. Trifonov, E. Kaxiras and M. D. Lukin, *Properties of nitrogen-vacancy centers in diamond: the group theoretic approach*, New J. Phys. **13**, 025025 (2011).

Intense fields… Th-210

A HHG interferometer with XUV and zeptosecond precision

D. E. Laban[1,2], A. J. Palmer[1,2], N. S. Gaffney[1,2], W. C. Wallace[1,2], M. G. Pullen[1,2], H. M. Quiney[3], I. V. Litvinyuk[2], D. Kielpinski[1,2], and R. T. Sang[1,2,*]

1. ARC Centre of Excellence for Coherent X-Ray Science, Griffith University, Brisbane, Australia
2. Australian Attosecond Science Facility, Griffith University, Brisbane, Australia
3. ARC Centre of Excellence for Coherent X-Ray Science, University of Melbourne, Melbourne, Australia
**r.sang@griffith.edu.au*

Experiments were performed to characterise an extreme-ultraviolet (XUV) interferometer formed by placing dual gas targets successively in a few-cycle laser focus. XUV is emitted via the nonlinear high-order harmonic generation (HHG) process in each target and varying the position of the target in the focus controls the relative phase between these emissions. Observations have been made on several harmonics from the plateau to the cut-off regions as the gas target separation, and hence relative phase, is varied. The physical mechanism behind the phase delay is understood with a semi-classical interpretation of the HHG process [1] and is predominantly found to arise from a time delay in the electron recombining due to the Gouy phase. The Gouy phase has the role of shifting the carrier-envelope phase of the few-cycle pulse as the beam passes through a focus [2]. This interferometric apparatus has an unprecedented precision; the timing resolution of the electron recombination delay has been measured to better than 100 zeptoseconds.

References

[1] Lewenstein, M., *et al.*, “Theory of high-harmonic generation by low-frequency laser fields”, PRA **49**, 2117 (1994).
[2] Lindner, F., *et al.*, “Gouy Phase Shift for Few-Cycle Laser Pulses”, PRL **92**, 113001 (2004).

Coherent transfer of optical orbital angular momentum in Raman sideband generation

J. Strohaber[1], M. Zhi, A. A. Kolomenskii, A. Sokolov, G. G. Paulus[1,2], and H. A. Schuessler[1]

1.Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA
2. Institut für Optik und Quantenelektronik Max-Wien-Platz 1, 07743 Jena, Germany
**jstroha1@physics.tamu.edu*

Optical vortices have attracted considerable attention in the past decade due to applications such as optical spanners, super resolution imaging, and entangled quantum states in quantum optics. We are interested in investigating the intense-field interaction of optical orbital angular momentum (OAM) carrying beams with matter. What role OAM plays in ultrafast intense-field processes is still experimentally largely unexplored. We have generated broadband Raman sidebands in Raman-active crystals with the goal of synthesizing few cycle femtosecond pulses as well as arbitrary waveforms. In particular, we have recently realized the coherent transfer of OAM in the selectively excited Raman transitions in a $PbWO_4$ crystal by using a pair of time-delayed linearly chirped pulses. This work was supported by the Welch Foundation (No. A1546) and the NSF (No. 0722800).

Reference

[1] F. Lenzini, S. Residori, F. T. Arecchi, and U. Bortolozzo, "Optical vortex interaction and generation via nonlinear wave mixing," Phys. Rev. A **84**, 061801 (2011).

Double photo-ionization of hydrogen molecule from the viewpoint of the time-delay theory

I. A. Ivanov[1,*], A. S. Kheifets[1], and V. V. Serov[2]

1.Research School of Physical Sciences, The Australian National University, Canberra ACT 0200, Australia
2. Department of Theoretical Physics, Saratov State University, 83, Astrakhanskaya, Saratov 410012, Russia
**igor.ivanov@anu.edu.au*

We present results of a timing analysis of the process of two-electron photo-ionization of the hydrogen molecule. Time dependent Schrödinger equation (TDSE) for the hydrogen molecule in presence of the laser pulse is solved numerically [1]. Projecting solution of the TDSE on the suitably prepared wavepacket states representing two electrons in continuum, we can study motion of ionized electrons in time. Unlike the simpler case of photoionization of the helium atom [2], timing analysis of the photoionization of hydrogen molecule reveals a more complicated picture, where details of the electron motion depend on the angles between velocities of the escaping electrons and molecular axis. Study of the angular dependence of the time-delays reveals features which can be interpeted as signatures of knock-out mechanism at work in the process of double photo-ionization of H_2 molecule.

References

[1] I. A. Ivanov and A. S. Kheifets *Time-dependent calculations of double photoionization of the aligned H_2 molecule*, Phys. Rev. A **85**, pp. 013406 (2012).
[2] A. S. Kheifets, I. A. Ivanov and Igor Bray *Timing analysis of two-electron photoemission*, J. Phys. B **44**, pp. 101003 (2011).

Interferences in resonant laser-atom pump and probe ionization process

V. D. Rodríguez[1,*], M. G. Bustamante[1], and R. O. Barrachina[2]

1. Departamento de Física and Instituto de Física de Buenos Aires, FCEyN, Universidad de Buenos Aires, 1428 Buenos Aires Argentina
2. Centro Atómico Bariloche and Instituto Balseiro (Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo), 8400 S. C. de Bariloche, Río Negro, Argentina
**vladimir@df.uba.ar*

We investigate theoretically a pump and probe laser atom setup. Similar to a recent proposal [1] we use a single strong laser pulse in resonance between the initial ground state with an excited state. The laser serves as a pump creating a coherent state mostly described by Rabi flopping between the two resonant states. Different from [1] the same laser pulse probes the electron by ionizing it through a concurrent multiphoton process. As expected the above threshold ionization peaks split up in Autler-Townes doublets. We focus on an interference process we have detected in-between each doublet by numerically solving the time dependent Schrödinger equation. We propose a theory that explains both quantitative and qualitatively the ionization spectrum. The theory is based on a Demkov's variational principle. The final trial wave function is given by Coulomb-Volkov one. The initial trial wave function is modeled by the coherent bound state obtained by solving the close-coupling equations accounting for decay towards the continuum.

Reference

[1] G. L. Yudin *et al.*, "Attosecond photoionization of coherently coupled electronic states", Phys. Rev. A **72**, 51401 (2005).

Intense fields Th-214

High suppression in strong-field ionization of fullerene C_{60}

Vladimir Usachenko[1,2,*], Pavel Pyak[2], and Vyacheslav Kim[3]

1. Institute of Applied Physics, National University of Uzbekistan, Tashkent, Uzbekistan
2. Physics Department, National University of Uzbekistan, Tashkent, Uzbekistan
3. Institute of Ion-Plasma and Laser Technologies, Tashkent, Uzbekistan
**vusach@yahoo.com*

The strong-field process of multiphoton *above-threshold ionization* (ATI) in laser-irradiated molecule of carbon fullerene C_{60} is addressed theoretically within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA) [1]. Our VG-SFA calculation results demonstrate a high suppression in C_{60} ionization as compared to ionization of "counterpart" atomic species having a nearly identical ionization potential (≈ 7.6 *eV*). In particular, for *Ti:Sapphire* laser pulse of wavelength $\lambda \approx 800$ *nm* and $\tau = 35$ *fs* of pulse duration, the strong-field ionization of C_{60} has been found to reach saturation at laser peak intensity $I \approx 2\cdot 10^{14}$ W/cm^2. that is in a perfect consistence with the respective value found in relevant experiment [2].

References

[1] Vladimir I. Usachenko, Pavel E. Pyak and Vyacheslav V. Kim. "Comparative study of strong-field ionization in laser-irradiated F_2 and other diatomic molecules: Density-functional-theory-based molecular strong-field approximation", Phys. Rev. A **79**, p. 023415 (2009).
[2] M. Tchaplyguine *et al.* "Ionization and fragmentation of C_{60} with sub-50 fs laser pulses", J. Chem. Phys. **112**, pp. 2781-2789 (2000).

Quantum oscillations in rotating ultracold Fermi gases

Charles Grenier[1], Corinna Kollath[2], and Antoine Georges[1,3,4]

1. Centre de Physique Théorique, Ecole Polytechnique, CNRS, 91128 Palaiseau Cedex, France
2. DPT-MaNEP, University of Geneva, CH-1211 Geneva, Switzerland
3. Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France
4. DPT-MaNEP, University of Geneva, CH-1211 Geneva, Switzerland

Rotating ultracold quantum gases have been a recurrent subject of interest over the last years. In this work, we studied the influence of rotation on the angular momentum of a noninteracting Fermi gas at low temperature. We show that, at low temperature, quantum contributions to the angular momentum emerge. These contributions are analogues of the de Haas - van Alphen oscillations in the solid-state context.

Th-216 Other

Long-term frequency stabilization system for external cavity diode laser based on mode boundary detection

Zhouxiang Xu, Kaikai Huang, and Xuanhui Lu

Physics Department, Zhejiang University, Hangzhou, 310027, P. R. China
**xhlu@zju.edu.cn*

We have implemented a long-term frequency stabilization system for external cavity diode laser (ECDL) based on mode boundary detection method. In this system, the saturated absorption spectroscopy was used. The current and the grating of the ECDL were controlled by a computer-based feedback control system. By checking any mode boundaries in the spectrum, the control system determined how to adjust current to avoid mode hopping. This procedure was executed periodically to ensure the long-term stabilization of ECDL in the absence of mode hops. This diode laser system without antireflection-coating had operated in the condition of long-term mode hopping free stabilization for almost 1000 hours, which is a significant improvement of ECDL frequency stabilization system. This technique is very useful in some applications such as high stability of laser power.

References

[1] C. E. Wieman and L. Hallberg, Rev. Sci. Instrum. **62**, 1-20 (1991).
[2] A. S. Arnold, J. S. Wilson, and M. G. Boshier, Rev. Sci. Instrum. **69**, 1236-1239 (1998).
[3] J. Hult, I. S. Burns, and C. F. Kaminski, Appl. Opt. **44**, 3675-3685 (2005).
[4] C. Petridis, *et al.*, Rev. Sci. Instrum. **72**, 3811-3815 (2001).
[5] Sheng-wey Chiow, Quan Long, Christoph Vo, Holger Müller, and Steven Chu, Appl. Opt. **46**, 7997-8001 (2007).

Photonic band gaps and distributed feedback lasing in cold atoms

W. Guerin[1,*], A. Schilke[1], Ph. W. Courteille[2], and C. Zimmermann[1]

1. Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
2. Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, Brazil
**william.guerin@pit.uni-tuebingen.de*

We investigate the photonic properties of cold atomic samples that are trapped in a one-dimensional (1D) optical lattice. The atoms build a 1D periodic structure and such an arrangement is expected to create a photonic band gap. We have experimentally observed this band gap by measuring a Bragg reflection as efficient as 80%, and we have studied the intrinsic limitations of such systems [1]. We also combined this system with electromagnetically-induced transparency, which allowed us to obtain a tunable and spectrally very narrow atomic Bragg mirror [2].

In a following experiment, we induced gain (by an appropriate pumping mechanism) in the atomic grating. The combination of gain and distributed feedback due to multiple Bragg reflection in the structure lead to the first cold-atom-based mirrorless laser [3], a topic of high current interest in the photonics community.

References

[1] A. Schilke, C. Zimmermann, Ph. W. Courteille and W. Guerin, *Photonic Band gaps in One-Dimensionally Ordered Cold Atomic Vapors*, Phys. Rev. Lett. **106**, 223903 (2011).
[2] A. Schilke *et al.*, to be published.
[3] A. Schilke, C. Zimmermann, Ph. W. Courteille and W. Guerin, *Optical parametric oscillation with distributed feedback in cold atoms*, Nature Photon. **6**, 101–104 (2012).

Other Th-218

Broadband Faraday isolator

Michal Berent[1,2,*], Andon A. Rangelov[1], and Nikolay V. Vitanov[1]

1. Department of Physics, Sofia University, James Bourchier 5 Blvd., 1164 Sofia, Bulgaria
2. Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznan, Poland
**mberent@amu.edu.pl*

Drawing on an analogy with the powerful technique of composite pulses in quantum optics [1] and polarization optics [2,3] we present a broadband optical diode (optical isolator) made of a sequence of ordinary 45° Faraday rotators sandwiched with quarter-wave plates rotated at the specific angles with respect to their fast polarization axes.

References

[1] B. T. Torosov and N. V. Vitanov, "Smooth composite pulses for high-fidelity quantum information processing", Phys. Rev. A 83, 053420 (2011).
[2] A. Ardavan, "Exploiting the Poincare-Bloch symmetry to design high-fidelity broadband composite linear retarders", New J. Phys. **9**, 24 (2007).
[3] S. S. Ivanov, A. A. Rangelov , N. V. Vitanov, T. Peters and T. Halfmann, "Highly efficient broadband conversion of light polarization by composite retarders" J. Opt. Soc. Am. A **29**, 265 (2012).

Multistability in a BEC-cavity system with raman coupling

S. Safaei[1,*], Ö. E. Müstecaplıoğlu[2], and B. Tanatar[1]

1. Department of Physics, Bilkent University, Bilkent, 06800 Ankara, Turkey
2. Department of Physics, Koç University, Sarıyer, 34450 Istanbul, Turkey
**safaei@fen.bilkent.edu.tr*

We consider a Bose-Einstein condensate, with atoms in two degenerate modes due to their internal hyperfine spin degrees of freedom, in a one-dimensional optical cavity. The two internal modes of the condensate atoms are coupled to the cavity field and an external transverse laser field in a Raman scheme. A parallel laser is also exciting the cavity mode. When the pump laser is far detuned from its resonance atomic transition frequency, an effective nonlinear optical model of the cavity-condensate system is developed under Discrete Mode Approximation (DMA), while matter-field coupling has been considered beyond the Rotating Wave Approximation. By analytical and numerical solutions of the nonlinear dynamical equations, we examine the mean cavity field and population difference (magnetization) of the condensate modes. The stationary solutions of both the mean cavity field and normalized magnetization demonstrate bistable behavior (multistability) under certain conditions for the laser pump intensity and matter-field coupling strength.

Today's accuracy of electron affinity measurements

Cyril Drag*, Mickaël Vandevraye, and Christophe Blondel

Laboratoire Aimé Cotton, CNRS/Université Paris-Sud, Orsay, France
**cyril.drag@lac.u-psud.fr*

Laser photodetachment threshold (LPT) detection and laser photodetachment microscopy (LPM) are presently the most accurate techniques used to measure atomic electron affinities.

Photodetachment microscopy has now produced electron affinity measurements for 13 years, and set a new standard for the accuracy of electron affinity measurements. The electron affinity of Sulfur (^{32}S) is now known to be 1 675 297.53(41) m^{-1} or 2.077 104 0(6) eV, which is the record in accuracy and even makes it possible to investigate the isotope shift of electron affinities [1]. More recently the electron affinity of Selenium was measured to be 1 629 727.6(9) m^{-1}, or 2.020 604 6(11) eV [2].

Both LPT and LPM techniques, however, most easily apply when photodetachment releases an electron *s*-wave. Today's challenge is to apply photodetachment microscopy to the case of *p*-wave photodetachment, which would introduce an additional degree of freedom in the electron interferograms.

References

[1] T. Carette, C. Drag, O. Scharf, C. Blondel, C. Delsart, C. Froese~Fischer, and M. Godefroid, "Isotope shifts in the sulfur electron affinity: observation and theory", Phys. Rev. A **81**, 042522 (2010).
[2] M. Vandevraye, C. Drag, and C. Blondel, "Electron affinity of selenium measured by photodetachment microscopy", Phys. Rev. A **85**, 015401 (2012).

Author Index

Notes

Notes

Notes

Notes

Notes

Notes

Notes

Notes

Notes

Notes