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).

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 $\mu g/\sqrt{\mathrm{Hz}}$ [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).

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).

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).

Th-016 Atomic clocks

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.

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 $1s^22s\ ^2$S, –7.354 098 421 444 37(1) a.u. for $1s^23s\ ^2$S, –7.318 530 845 998 91(1) a.u. for $1s^24s\ ^2$S, –7.410 156 532 652 4(1) a.u. for $1s^22p\ ^2$P, and –7.335 523 543 524 688(3) a.u. for $1s^23d\ ^2$D. 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, $E_{\mathrm{eff}} = KE_0$, 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.

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).

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).

Th-064 Bose gases

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 mF = 0 level below the average of the mF = ±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.

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.

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).

Optical lattices Th-102

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.

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).

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).

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).

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 $\left|\uparrow\right\rangle = \left|F=4, m_F=0\right\rangle$ clock state and apply a weak excitation pulse, resonant with the $\left|F=4, m_F=0\right\rangle \rightarrow \left|F'=4, m'_F=+1\right\rangle$ 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 $\left|\downarrow\right\rangle = \left|F=3, m_F=0\right\rangle$ clock level and the collective quantum state of the example is now described by $\left|\psi\right\rangle = \sum_{i=1}^{N_a}\left|\uparrow\uparrow\cdots\uparrow\downarrow_i\uparrow\cdots\uparrow\right\rangle$. We then apply a microwave π/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).

Quantum optics… Th-138

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 ± 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 $a = a_{\text{bg}}\left[1 + \Delta B / (B - B_0)\right]$ 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:

$$a = \left[a_{\text{bg}} + \frac{\bar{\Gamma}/2}{E_{\text{R}}}\left(\bar{a}\frac{a_{\text{bg}} - \bar{a}}{b} - b\right)\right]\left[1 + \frac{\bar{\Gamma}/2}{E_{\text{R}}}\left(\frac{a_{\text{bg}} - \bar{a}}{b}\right)\right]^{-1}.$$

$a_{\text{bg}} \in (-\infty, +\infty)$ 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 ~ 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 ($\frac{\Delta_{res}}{B_{res}} \approx 10^{-5}$), 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 $\frac{\Delta_{res}}{B_{res}}$ 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).

Cold neutral… Th-170

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).

Cooling and trapping… Th-186

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).

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 Δm=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).

Atoms in external fields Th-202

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 $\Delta m = 1$ 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).

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 photo-ionization 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).

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 $I \approx 2\cdot10^{14}$ 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).

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).