Invited Talks

Quantum simulations with ultracold bosons and fermions

Wolfgang Ketterle[1]

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

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

Anderson localization of ultra-cold atoms

Alain Aspect

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

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

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

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

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

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

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Probing the contact locally in a trapped unitary Fermi gas

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

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

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

Strongly interacting Fermi gases: thermodynamics and topological phases

Martin W. Zwierlein

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

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

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Thermodynamics of quantum gases

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

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

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

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The electric dipole moment of the electron

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

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

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

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Physics with trapped antihydrogen

J. S. Hangst

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

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

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

V. V. Flambaum

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

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

Precision metrology and many-body quantum physics

Jun Ye

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

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

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

Roman Schnabel

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

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

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Building a metrological toolbox for harnessing atoms and molecules

Paolo De Natale[1,2]

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

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

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Quantum networks of atoms

Christopher Monroe

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

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

Towards large-scale entanglement in a string of trapped ions

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

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

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

Reference

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

Stefan Kuhr[1,2]

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

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

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Progress towards measuring the electron EDM with thorium monoxide

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

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

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

Reference

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

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

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

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

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Frequency metrology in quantum degenerate helium

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

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

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

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Cavity Quantum Electrodynamics with real and artificial atoms

Serge Haroche

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

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

Invited Talk Quantum optics and cavity QED

Quantum network with individual atoms and photons

Gerhard Rempe

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

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

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

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

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

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

Quantum storage and manipulation using gradient echo memory

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

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

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

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Tunable gauge potential for spinless particles in driven lattices

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

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

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

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

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A superradiant laser with <1 intracavity photon

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

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

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

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Interaction-based spin measurements in a cold atomic ensemble

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

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

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

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Atoms and molecules… Invited Talk

Exploring and controlling quantum gases under extreme conditions

Immanuel Bloch[1,2]

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

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

Altered interactions in artificial gauge fields

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

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

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

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Transport of impurities in optical lattices

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

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

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

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Three universal trimers in ultracold atoms

Masahito Ueda

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

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

Tunable, deterministic few-fermion quantum systems

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

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

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

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

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

New physics with dipolar gases

Gora Shlyapnikov

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

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

Hot topic Ultracold gases

Quantum degenerate Bose and Fermi dipolar gases of dysprosium realized

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

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

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

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Bose-Einstein condensation of erbium

F. Ferlaino

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

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

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Spin and density response of strongly interacting Fermi gases

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

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

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

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Atomic physics with attosecond pulses

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

Department of Physics, Lund University, Sweden

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

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

Reference

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Dynamics of electron wavepacket following tunnel ionization

Alexandra Landsman* and Ursula Keller

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

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

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Ultrafast AMO physics at the LCLS x-ray FEL

Philip H. Bucksbaum

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

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

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Beyond atomic physics Invited Talk

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

Mikhail Lukin

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

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

Single molecule nanometry for biological physics

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

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

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

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Quantum coherent coupling of light and mechanical motion

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

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

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

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Theory and experiments with quantum fluids of light

Iacopo Carusotto

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

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

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

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

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Attosecond control of collective charges in plasmas

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

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

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

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Hybrid atom-membrane optomechanics

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

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

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

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

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Feedback in a cavity QED system for control of quantum beats

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

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

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

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