Dynamical transport control of matter waves in two-dimensional optical lattices

J.A. Abdullaev[1], D. Poletti[2], E.A. Ostrovskaya[1] Y.S. Kivshar[1]

[1]*Nonlinear Physics Centre and ARC Centre of Excellence for Quantum-Atom Optics, Research School of Physics and Engineering, The Australian National University, Canberra ACT 0200, Australia*

[2]*Centre for Quantum Technologies, National University of Singapore, Singapore 117542, Republic of Singapore*

In recent years optical lattices (OL) have been proven to be a powerful tool for manipulating and controlling stable, spatially localized matter waves, due to the interplay of the nonlinearity of the matter wave and the periodicity of the lattice. Such a control is a very important goal from the viewpoint of emerging integrated technologies based on the use of ultracold atomic gases - Bose-Einstein condensates[1].

We analyze the mechanism for controlled transport of two-dimensional matter-wave solitons, created in a Bose-Einstein condensate of atoms with a negative scattering length. The transport is realized by means of a rocking two-dimensional OL[2], where the term rocking refers to time-periodic shaking of the lattice[3].Our analysis is carried out within the mean-field approximation through the numerical solution of the two-dimensional Gross-Pitaevskii (GP) equation:

$$i\frac{\partial\psi}{\partial t} + \nabla_{\perp}^2\psi + |\psi|^2\psi + V_{\rm OL}(\mathbf{r},t)\psi = 0, \tag{1}$$

where $V_{\rm OL}(\mathbf{r},t) = V_0\cos[x - X(t)]\cos[y - Y(t)] + V_x\cos[2x - X(t)] + V_y\cos[2y - Y(t)]$. Numerical calculations and the theory based on the time-averaging approach, demonstrate that fast time-periodic rocking of the two-dimensional OL enables efficient stabilization and manipulation of spatially localized matter wavepackets via induced reconfigurable mobility channels[4].

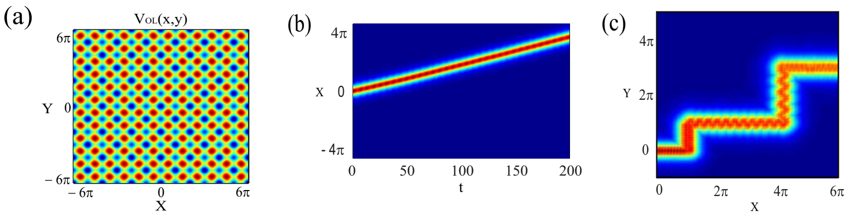

Figure 1: *(Color online) (a) Rocking optical lattice potential at t=0. (b) Dynamics of a moving soliton in a rocking optical lattice potential along X direction. (c) Centre of mass trajectory of a moving soliton in a rocking optical lattice along X and Y directions.*

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Ab initio study of ground and low-lying excited states of CaH^+ molecule

M. Abe[1], M. Kajita[2], Y. Moriwaki[3] M. Hada[1]

[1]*Department of Chemistry, Tokyo Metropolitan University, Hachioji, Japan*
[2]*National Institute of Information and Communications Technology, Koganei, Tokyo*
[3]*Department of Physics, University of Toyama, Toyama, Japan*

The grand unification theory (GUT) implies a possibility of time-variance of proton-to-electron mass ratio (m_p/m_e). Hence, the detection of the variance of m_p/m_e is an attractive research topic, and one possible way for the detection is highly precise spectroscopic measurements of molecules in laboratory. Kajita and Moriwaki showed the molecular vibrational transition frequency of $^{40}CaH^+$ is observable within 10^{-15} uncertainty, and a suitable system for the detection of m_p/m_e.[1] This laboratory experiment is an ongoing project by themselves. Although CaH^+ is a simple diatomic molecule, there are no experimental data so far. Hence, we calculated CaH^+ potential energy curves using an *ab initio* method in the present work, to provide basic information for this experiment. We adopted the cc-PCV5Z and cc-PV5Z basis set for Ca and H, respectively. We performed state-averaged complete active space self consistent field theory (SA-CASSCF) within the non-relativistic framework. Two valence electrons in 10 orbitals (composed by 4s, 4p, and 3d of Ca and 1s of H atomic orbitals) are chosen for CAS. Electron correlation energy has been improved by the complete active space second-order perturbation theory (CASPT2). MOLCAS 7.2 software is used for all the calculations. Calculated excitation energies in Ca^+–H 100 bohr distance are 13799~13910 (cm^{-1}) for the first excitation level and 25240~25246 (cm^{-1}) for the second excitation level. These values are comparable with the experimental atomic spectra of Ca^+: 13650.20 ($^2D_{3/2}$), 13710.89 ($^2D_{5/2}$), 25191.518 ($^2P_{1/2}$), and 25414.414 ($^2P_{3/2}$) in cm^{-1}. Our calculated results are reasonably close to the experimental ones in around 200 cm^{-1} difference. The obtained potential energy curves suggest that triplet states are weakly bound or completely repulsive comparing to the singlet states. In singlet states, Σ states are more deeply bound and have a lot of vibrational levels than the Π and Δ states. We will propose theoretical spectroscopic parameters and discuss the transition dipole moments and oscillator strengths in our presentation.

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A pT-scale magnetic micro-gradiometer based on absorption detection of diamond NV centers

V. M. Acosta[1], E. Bauch[1,2], L. J. Zipp[1], A. Jarmola[1,3], M. P. Ledbetter[1], D. Budker[1,4]

[1]*Department of Physics, University of California, Berkeley, CA 94720*
[2]*Technische Universität Berlin, Hardenbergstraße 28, 10623 Berlin, Germany*
[3]*Laser Centre, University of Latvia, Rainis Blvd. 19, Riga LV-1586, Latvia*
[4]*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720*

In the last two years a new technique for measuring magnetic fields at the micro- and nano-meter scale has emerged based on optical detection of nitrogen-vacancy (NV) electron spin resonances in diamond [1,2]. This technique offers the possibility to measure magnetic fields from a single electron spin, and perhaps even a single nuclear spin, in a wide temperature range from liquid-helium to well beyond room temperature. Sensors employing ensembles of NV centers promise the highest sensitivity[3], and pilot NV-ensemble magnetometers have very recently been demonstrated by several groups. We demonstrate a technique to read out the NV spin state using infrared optical absorption at 1042 nm. With this technique, measurement contrast and collection efficiency can approach unity, leading to an overall increase in magnetic sensitivity compared to the traditional method of collecting fluorescence in the red. Preliminary measurements at 45 K on a sensor with active area $\sim 30\times30\times1000\ \mu\mathrm{m}^3$ reveal magnetic resonances with amplitude and width corresponding to a shot-noise-limited sensitivity of a few $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ (Fig. 1). We use this technique to operate a dual-channel gradiometer prototype that is well-matched for detection of J-coupling spectra in microfluidic NMR chips[4]. This work was supported by NSF grant PHY-0855552.

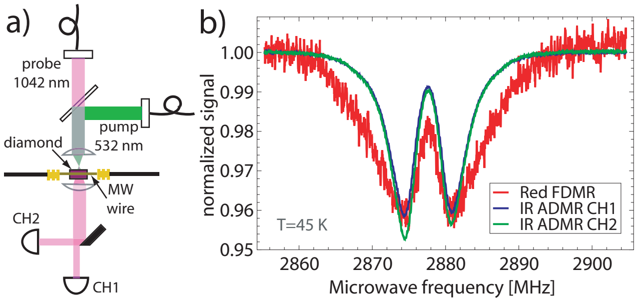

Figure 1: *(a) IR absorption gradiometer apparatus. The green pump and IR probe beams are focused to a diameter of* $\sim 30\ \mu\mathrm{m}$ *near the surface of the diamond, and two halves of the transmitted IR beam are detected with separate photodiodes. (b) Zero-field optically-detected magnetic resonance at* 45 *K using the traditional red fluorescence method (FDMR) and both channels of the IR absorption-probe gradiometer (ADMR).*

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Bose-Einstein Condensation in Microgravity

H. Ahlers[1], E.M. Rasel[1], the QUANTUS-Team[1,2,3,4,5,6,7,8,9],

[1]*Institute of Quantum Optics, Leibniz University Hannover, Germany*
[2]*ZARM, Uni Bremen*
[3]*Institute of Physics, HU Berlin*
[4]*Institute of Laser Physics, Uni Hamburg*
[5]*Institute of Quantum Physics, Uni Ulm*
[6]*Max-Planck-Institute of Quantum Optics, Munich*
[7]*Institute of Applied Physics, TU Darmstadt*
[8]*Midlands Ultracold Atom Research Centre, University of Birmingham, UK*
[9]*Ferdinand-Braun-Institute, Berlin*

We report on the results of the QUANTUS-I free fall BEC experiment at the 110m ZARM drop tower in Bremen. Motivated by the prospect of performing precision interferometry with matter waves on long timescales, considerable efforts have been taken to develop a setup suitable for operation in the drop tower. This microgravity environment demands a robust and miniaturized setup that can sustain decelerations of up to 50g on a regular basis. After the first realization of a BEC in microgravity, over 180 drops have been performed so far. Our atom-chip based trap can produce extremely shallow traps in microgravity, leading to a slow expansion and allowing us to observe the condensates for up to 1 s of free evolution. The expansion data are presented together with the predictions of a detailed model of the experiment.

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Possible Enhanced Sensitivity to the Time Variation of Fundamental Constants in SiBr

K. Beloy[1], A. Borschevsky[1], V. Flambaum[2,1], P. Schwerdtfeger[1]

[1]*Centre for Theoretical Chemistry and Physics, The New Zealand Institute for Advanced Study, Massey University Auckland, Private Bag 102904, 0745, Auckland, New Zealand*
[2]*School of Physics, University of South Wales, Sydney 2052, Australia*

Theories unifying gravity with other interactions suggest the possibility of spatial and temporal variation of fundamental physical constants, such as the fine structure constant, $\alpha = e^2/\hbar c$, and the proton-to-electron mass ratio, $\mu = m_p/m_e$[1]. Search for such variation has received considerable interest in recent years, and is being conducted using a wide variety of methods[2].

Precision molecular spectroscopy is a new and promising direction of search for variation of fundamental constants. Molecular spectra are sensitive to both μ and α, and by measuring close lying levels great enhancement of relative variation may be observed. In particular, diatomic molecules that have a near cancellation between hyperfine structure and rotational intervals or between fine structure and vibrational intervals are of interest in the context of such an enhancement[3].

SiBr molecule has the favorable quality of a near cancelletion between the fine structure and vibrational interval in a ground state multiplet. Here we take a closer examination of SiBr as a candidate for detecting variations in α and μ. We analyze the rovibronic spectrum by employing the most accurate experimental data available in the literature and perform *ab initio* calculations to determine the precise dependence of the spectrum on variations in α. Furthermore, we calculate the natural linewidths of the rovibronic levels, which place a fundamental limit on the accuracy to which variations may be determined.

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A multiplexed optical link for ultra-stable frequency dissemination

O. Lopez[1], A. Haboucha[2], A. Amy-Klein[1], H. Jiang[2], B. Chanteau[1], F. Kéfélian[1], V. Roncin[1], G. Santarelli[2], C. Chardonnet[1]

[1]*Laboratoire de Physique des Lasers, CNRS, Université Paris 13, 99 av. J.-B. Clément, 93430 Villetaneuse, France*
[2]*LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, 61 Av. de l'Observatoire, Paris, France*

The transfer of ultra-stable frequency signal between distant laboratories is required by many applications in time and frequency metrology, fundamental physics, particle accelerators and astrophysics. Frequency transfer using the optical phase of an ultra-stable laser over a dedicated fiber link was reported on distances up to about 200 km by several groups. The present challenge is to extend this method of frequency dissemination on longer distances in order to connect laboratories of different countries.

For this purpose, we have recently developed a novel dissemination approach over non-dedicated fibers[1]. We take advantage of the existing Internet fiber network already connecting every laboratory via the National Research Networks. The ultra-stable frequency signal is propagating simultaneously with the Internet traffic in the same fiber using one dedicated wavelength in a dense wavelength division multiplexing (DWDM) approach.

With Internet fibers, we have a very limited control on the fiber network and the attenuation and noise is likely to be higher than with dedicated fibers, which can limit the transfer to a few hundreds of km. For longer distances, we have foreseen the segmentation of the link into several cascaded sections. In that case, a repeater station should be used between the different segments of the link. This multiple sub-link approach allows for an increased correction bandwidth and robustness regarding attenuation.

We demonstrate the ultra stable transfer of an optical frequency over 300 km of installed optical fibers by cascading two 150 km segments connected by an autonomous regeneration station. This ultrastable optical link uses an optical telecommunication network simultaneously carrying Internet data and goes through two Data Center Facilities using several optical wavelength multiplexers and bidirectional erbium-doped fiber amplifiers. We have obtained an instability of 3×10^{-15} at 1 s measurement time which scales down to about 7×10^{-20} after about 20 hours. These results are very promissing and represent an intermediate step for the future development of continental-scale frequency transfer.

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Measurement of the Boltzmann constant by the Doppler Broadening Technique at the 10^{-5} accuracy level

M. Triki[1], C. Lemarchand[1], C. Daussy[1], S. Briaudeau[2], B. Darquié[1], A. Amy-Klein[1], C. Chardonnet[1], CH.J. Bordé[1]

[1]*Laboratoire de Physique des Lasers, CNRS, Université Paris 13, 99 av. J.-B. Clément, 93430 Villetaneuse, France*
[2]*Institut National de Métrologie, LNE-INM, CNAM, 61, rue du Landy, 93200 Saint-Denis, France*

The present primary reference for the unit of temperature is the triple point of water which implies a specific property of macroscopic matter. At the microscopic scale, the temperature can be related through the Boltzmann constant k_B to the mean energy per particle and per degree of freedom. This energy may itself be related to a frequency via the Planck constant h. Finally, temperature and frequency are connected by k_B and h and fixing the value of k_B would connect the temperature and time units. But, before fixing the value of the Boltzmann constant, it is necessary to verify precisely the consistency of the value of k_B in the present context. Until now, the recommended value in CODATA $k_B = 1.3806504(24) \times 10^{-23}$ J.K^{-1} is derived from the value of ideal gas constant R and the Avogadro constant N_A by the relation $k_B = R/N_A$. The relative uncertainty of k_B is 1.7×10^{-6}.

We have developed in our group a new approach for measuring the Boltzmann constant by laser spectroscopy. The idea is to record by laser spectroscopy the Doppler profile of a well-isolated atomic or molecular absorption line of a gas in a cell at a well-controlled temperature. This profile will reflect the Maxwell-Boltzmann distribution of the longitudinal velocity distribution along the laser beam axis. A straightforward line analysis which can take into account residual pressure broadening, hyperfine structure, etc, leads to a determination of the Doppler broadening, proportional to $\sqrt{k_T}$, and thus to k_B.

We report our progress in the direct determination of the Boltzmann constant by laser spectroscopy. The value of k_B is inferred from the Doppler profile of the linear absorption line in an ammonia vapour. Ammonia is contained in an absorption cell located inside a thermostat operating with an ice-water mixture at a temperature around 273.15 K referenced to the triple-point of water. We have recorded the Doppler profile of the asQ(6,3) rovibrational line in the ν_2 band of $^{14}NH_3$, at $\nu = 28\,953\,694$ MHz. Our earlier measurements[1] yielded a value of the Boltzmann constant with an uncertainty of 2×10^{-4}.

Recent developments of the experimental set-up and a new approach to the data processing using a Voigt and/or a Galatry line shape will be described. The new determination of k_B has a relative uncertainty of 9×10^{-6} and possible systematic errors are presently explored to go beyond.

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Quantum Enhanced Metrology: Optimal Phase Estimation in Optical and Atomic Interferometry

U. Dorner[1,2] R. Demkowicz-Dobrzanski[3], B.J. Smith[2], K. Banaszek[3], I.A. Walmsley[2]

[1]*Centre for Quantum Technologies, National University of Singapore, Singapore 117543*
[2]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[3]*Institute of Theoretical Physics, University of Warsaw, ul. Hoza 69, PL-00-681 Warszawa, Poland*

The strong sensitivity of certain quantum states to small variations of external parameters opens up great opportunities for devising high-precision measurements with unprecedented accuracy, ideally leading to an improvement from the *standard quantum limit* to the *Heisenberg limit*. A particularly important physical measurement technique is interferometry which has countless applications in science and technology. Understanding limits on its performance in realistic situations, i.e. in the presence of unwanted noise, is therefore of great importance.

We therefore investigate possibilities for improved phase estimation in optical[1,2] and atomic (Ramsey type) interferometers using highly non-classical input states. In particular, this includes the determination of the fundamental limits of the achievable precision in the presence of noise which is experimentally unavoidable and threatens to destroy the employed quantum state and therefore potential improvements in precision. Dominant sources of noise are photon loss (in optical interferometers) and dephasing (in atomic interferometers, e.g. with Ions stored in Paul traps). The quantum states corresponding to these fundamental limits represent an optimal trade-off between robustness with respect to noise and quantum improvement in phase estimation. Although the found limits are generally worse than the Heisenberg limit, we show that the obtained precision beats the standard quantum limit, and can thus lead to a significant improvement compared to classical interferometers.

In addition to this, we discuss alternative states and strategies leading to slightly smaller precision but which are potentially easier to implement and therefore more relevant for experiments.

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Antihydrogen Clock

P. Froelich[1], A. Voronin[2],

[1] *Uppsala University, Dept. of Quantum Chemistry, Box 518, 75120 Uppsala, Sweden*
[2] *Lebedev Physical Institute, 53 Leninsky prospect, 117924 Moscow, Russia*

In view of difficulties in unifying quantum mechanics with the theory of gravity it is of great interest to investigate the gravitational acceleration for quantum mechanical objects, such as atoms. Such experiments have been already performed, e.g. using interferometric methods to test WEP for various isotops of Rubidium atoms [1]

However the experiments with *anti* atoms are even more interesting. This is because the modern theories striving to unify gravity and quantum mechanics (string theories among them) tend to suggest violation of the gravitational equivalence of particles and antiparticles. Experiments testing the gravitational properties of antiatoms are on the agenda of all experimental groups working with antihydrogen, see e.g. the programs of ALPHA, ATRAP and AEGIS collaborations.

In the present contribution we investigate the possibility to test gravitational properties of antiatoms in the ultimate quantum limit. We study antihydrogen atoms bouncing in the lowest gravitational states above material surface. The existence of such gravitational states for *neutrons* has been already demonstrated experimentally [2]. The existence of similar states for antiatoms seems counterintuitive in view of annihilation of antiatoms on the surface. We have however shown [3] that ultracold antihydrogen atoms are effectively reflected from the material surface due to so called quantum reflection from Casimir-Polder atom-surface interaction potential.

We show, that antihydrogen atoms confined from below by quantum reflection via Casimir forces, and from above by the gravitational force, will form metastable gravitational states. They will bounce on the surface for a finite life-time (on the order or 0.1 s). This simple system can be viewed as a microscopic laboratory for testing the gravitational interaction under extremely well specified (in fact, quantized) conditions.

The annihilation of antiatoms on the surface occurs with small but finite probability and gives clear and easy-to detect signal, which allows continuous monitoring of the density of antiatoms in the gravitational state as a function of time. In case when antiatoms are prepared in the superposition of gravitational states, the time-dependent behavior of the antiatom density shows beatings, determined by the *energy difference* between the gravitational levels. The measurement of such transition frequencies between the gravitational levels allows dertermination of the gravitational force Mg, acting on antiatoms. We show that the measurement of *differences* between energy levels would allow determination of Mg in a way independent from the effects of antiatom-surface interaction.

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Quantum non-demolition measurement and preparation of non-classical states of the light

S. Gleyzes[1], C. Sayrin[1], X. Zhou[1], B. Peaudecerf[1], I. Dotsenko[1,2], M. Brune[1], J.M. Raimond[1], S. Haroche[1]

[1]*Laboratoire Kastler Brossel, École Normale Supérieure, CNRS, Université P. et M. Curie, 24 rue Lhomond, F-75231 Paris Cedex 05, France*
[2]*Collège de France, 11 Place Marcelin Berthelot, F-75231 Paris Cedex 05, France*

Quantum cavity electrodynamics is a natural system for quantum information experiments. In our set-up we "trap" microwave photons in the mode of a very high finesse superconducting Fabry-Perot cavity. The very long lifetime of the photons (0.13 s) allows us to observe them with Rydberg atoms that cross the mode of the resonator. Each probe atom performs a quantum non-demolition (QND) measurement of the number of photons based on the dispersive interaction between the atom and the field. The Rydberg atoms act like little atomic clocks which are slowed down by the presence of photons in the mode. The delay they accumulate during the interaction is proportional to the intensity of the light, and its measurement using Ramsey interferometry allows us to determine non-destructively the number of photons.

The QND measurement of the number of photons is a powerful tool to both prepare and characterize non-classical states of the light. QND measurement of the number of photons of a coherent state projects the field onto a state of well-defined photon number, and therefore is a very efficient way to prepare many photon Fock states[1]. Once the state has been prepared, QND measurements (combined with coherent field injection in the mode of the resonator) allow to reconstruct the density matrix of the field in the cavity. Using this technique, we have been able to reconstruct the Wigner function of Fock states and record a movie of the decoherence of a Schödinger's cat state[2].

Finally, we have developed a quantum feedback scheme that will allow us to prepare deterministically Fock states with a given number of photons. Starting from a coherent state, we will use the partial information given by atomic probes to counteract in real time on the field using injection of classical pulses adjusted to increase the probability of the target photon number. With this combination of QND measurements and small coherent field injections, simulations show that we will after a few tens of iterations steer the field towards $|n_0\rangle$, and protect this state from decoherence[3].

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Direct spectroscopy of the 1557 nm 2^3S–2^1S transition in metastable helium

M.D. Hoogerland[1,3], R. van Rooij[1], J. Simonet[1,2], K.S.E. Eikema[1], W. Vassen[1]
[1]*Laser Centre Vrije Universiteit, De Boelelaan 1081, 1081HV Amsterdam, Netherlands*
[2]*École Normale Suprieure, 24 rue Lhomond, 75005 Paris, France*
[3]*University of Auckland, Private Bag 92019, Auckland, New Zealand*

We present the first direct measurement of the absolute transition frequency between the triplet and singlet metastable states of helium. This is a magnetic dipole transition, and strongly forbidden by electric dipole selection rules, which are extremely rigid for helium. The transition has a natural width of 8 Hz, determined by the two-photon decay of the singlet metastable to the ground state. The states involved are the two lowest excited states of the second most simple atom, and as such the exact value of their energies form a good test for modern QED theory. Our measurement agrees with these calculations, but we claim an accuracy that is two orders of magnitude better.

We trap ultracold metastable helium atoms (2^3S(m=+1)) in a dipole trap, and subsequently illuminate the atoms with a spectroscopy laser beam, typically for 2–8 seconds. If the spectroscopy beam is close to resonance with the transition to the singlet state, which is anti-trapped, we observe a strong trap loss. Both the trap and the spectroscopy beam are derived from the same, frequency tunable, erbium-doped fiber laser, at a frequency close to the 1557 nm transition in helium and with a short-term linewidth of 10 kHz.

To obtain an absolute frequency measurement, as well as long term stability, the frequency of this laser is locked to one of the modes of a femtosecond laser. The frequency comb is referenced to a GPS-controlled rubidium atomic clock. From our measurements of the transitions, we observe a long term line width of the spectroscopy laser of 30 kHz (rms).

We perform measurements for a range of trap laser and spectrocopy laser powers, allowing for an extrapolation to zero laser power. All measurements are corrected with precision determinations of the Zeeman shift, the recoil shift, and a possible mean field shift. The resulting value for the transition frequency is $f = 190,510,702,161(30)$ kHz. Our preliminary accuracy is mainly limited by drifts in the offset magnetic field.

We have also performed a similar measurement in metastable ^{3}He, for the transition from the $2^3\mathrm{S}_1(F = 3/2) \rightarrow 2^1\mathrm{S}_0(F = 1/2)$ states. This resonance is shifted by a hyperfine splitting and by an isotope shift, which is in turn determined by the change in the reduced mass of the electron, additional QED terms and a different charge radius of the nucleus. Our result for this transition frequency is $f = 192,504,914,455(30)$ kHz.

Both measurements are a confluence of a number of novel spectroscopic techniques and technologies, and challenge our current understanding of QED theory.

Process tomography of dynamical decoupling in a dense optically trapped atomic ensemble

I. Almog, Y. Sagi, N. Davidson

Weizmann Institute of Science, Rehovot 76100, Israel

An ensemble of two level quantum systems coupled to a fluctuating external environment is a common paradigm in many fields of study. This coupling leads to decoherence that limits the usefulness of these systems, e.g. as qubits in quantum computation systems. In cold atomic ensembles, which have many potential applications in quantum information, this problem is intrinsic since the fluctuations arise due to collisions which are inherent to the high densities required to achieve a good overall efficiency of quantum operations. Though fluctuations at low frequencies can be overcome by a single population inverting pulse, as the collision rate increases this is no longer possible due to higher frequency components. Dynamical decoupling (DD) theories generalize this technique to multi-pulse sequences by harnessing symmetry properties of the coupling Hamiltonian. Experimentally, multi-pulse sequences were first used in NMR and more recently in an ion-lattice model system and gamma-irradiated malonic acid single crystals. Here we report on experiments with optically trapped ^{87}Rb atoms demonstrating a 20-fold increase of the coherence time when a dynamical decoupling sequence with more than 200 π-pulses is applied. We perform quantum process tomography (QPT) and demonstrate that using the decoupling scheme a dense ensemble with an optical depth of 230 can be used as an atomic memory with coherence times exceeding 3 sec. We find that the optimal decoupling sequence for collisional fluctuations with a Lorentzian power spectrum is almost identical to the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence. In addition to their practical importance for future applications of cold atomic ensembles, our results constitute the first experimental demonstration of dynamical suppression of decoherence originating in self-interactions and not in a noisy external environment.

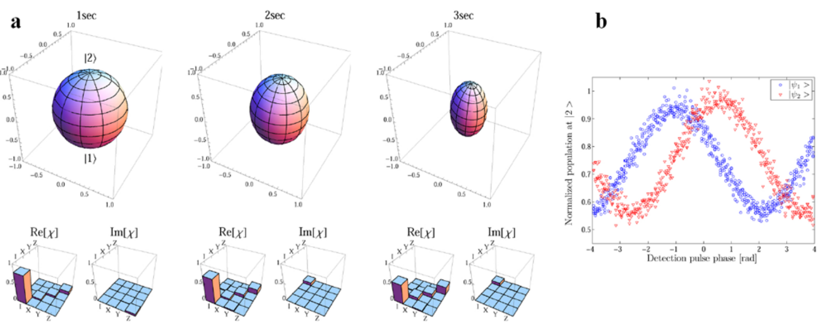

Figure a: *QPT of dynamical decoupling in a cold atomic ensemble with DD of 70Hz.*

Figure b: *Ramsey fringes for the two orthogonal states in the equatorial plain, showing that coherence is preserved for 3 sec for an arbitrary initial state.*

Experimental multiparticle entanglement dynamics induced by decoherence

J.T. Barreiro[1], P. Schindler[1], O. Gühne[2,3], T. Monz[1], M. Chwalla[1], C.F. Roos[1,2], M. Hennrich[1], R. Blatt[1],

[1]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
[2]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[3]*Institut für Theoretische Physik, Universität Innsbruck, 6020 Innsbruck, Austria*

Multiparticle entanglement leads to richer correlations than two-particle entanglement and gives rise to striking contradictions with local realism, inequivalent classes of entanglement, and applications such as one-way or topological quantum computing. When exposed to decohering or dissipative environments, multiparticle entanglement yields subtle dynamical features and access to new classes of states and applications. Here, using a string of trapped ions, we experimentally characterize the dynamics of entanglement of a multiparticle state under the influence of decoherence. By embedding an entangled state of four qubits in a decohering environment (via spontaneous decay), we observe a rich dynamics crossing distinctive domains: Bell-inequality violation, entanglement superactivation, bound entanglement, and full separability (see Fig. 1). We also develop new theoretical tools for characterizing entanglement in quantum states. Our techniques to control the environment can be used to enable novel quantum-computation, state-engineering, and simulation paradigms based on dissipation and decoherence [1].

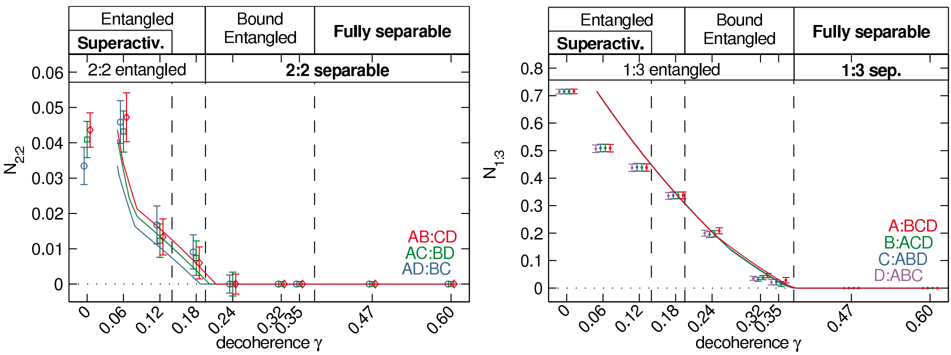

Figure 1: *Negativity for each 2:2 and 1:3 bipartition as a function of decoherence. Bipartitions data were slightly offset horizontally for clarity, but all visible groups correspond to the same amount of decoherence indicated by the tick marks. The solid lines were calculated by decohering the initial state with a 0.05 offset in γ. The properties shown in bold were determined by tests independent of the plotted data.*

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Multiqubit symmetric states with high geometric entanglement

J. Martin[1], O. Giraud[2,3,4,5], P.A. Braun[6,7], D. Braun[2,3], T. Bastin[1]

[1]*Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, Liège, Belgium*
[2]*Université de Toulouse; UPS; Laboratoire de Physique Théorique (IRSAMC); Toulouse, France*
[3]*CNRS; LPT (IRSAMC); Toulouse, France*
[4]*Université Paris-Sud, LPTMS, UMR8626, Université Paris-Sud, Orsay, France*
[5]*CNRS, LPTMS, UMR8626, Université Paris-Sud, Orsay, France*
[6]*Fachbereich Physik, Universität Duisburg-Essen, Duisburg, Germany*
[7]*Institute of Physics, Saint-Petersburg University, Saint-Petersburg, Russia*

We propose a detailed study of the geometric entanglement[1] properties of pure symmetric N-qubit states, focusing more particularly on the identification of symmetric states with a high geometric entanglement and how their entanglement behaves asymptotically for large N (see note[2]). We show that much higher geometric entanglement with improved asymptotical behavior can be obtained in comparison with the highly entangled balanced Dicke states studied previously (see Fig. 1). We also derive an upper bound for the geometric measure of entanglement of symmetric states. The connection with the quantumness of a state[3] is discussed.

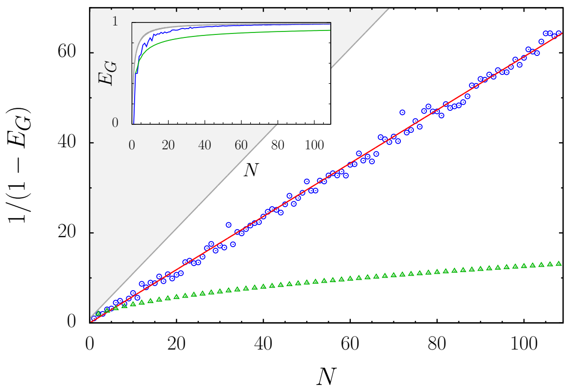

Figure 1: *Geometric entanglement E_G of symmetric states for the Coulomb arrangement*[2] *with respect to the number N of qubits (blue circles). Green triangles correspond to the geometric entanglement of the balanced Dicke states. The grey shaded area shows the domain ruled out by the derived upper bound for the geometric measure.*

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Continuous Variable Entanglement in Two Ultracold Atoms

T. Fogarty[1], J. Goold[1,2], M. Paternostro[3] and Th. Busch[1]

[1]*Department of Physics, University College Cork, Cork, Republic of Ireland*
[2]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, 117543, Singapore*
[3]*School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*

Techniques to trap, cool and control single atoms have over the past number of years improved to an extent that makes it possible to carry out high fidelity measurements on single or pairs of quantum particles. This has lead to many impressive experiments in the area of quantum information and brought significant progress to our understanding of the foundations of quantum mechanics.

The well known Einstein-Podolsky-Rosen (EPR) paradox is one of the issues at the heart of quantum mechanics. It describes the consequences of continuous variable entanglement between two particles and has, in recent years, been investigated extensively for systems of photons and ions. Using the Wigner phase-space representation of the two-particle state in question one can construct a measure of the correlations in the system, which then can be shown to violate a Bell-type inequality.

Here we apply this technique to the case of neutral, bosonic atoms and calculate the violation using an exactly solvable model for a pair of interacting ultracold particles in separate harmonic trapping potentials, whose dynamics is restricted to one spatial dimension. The model allows the distance between the traps and the point-like interaction strength between the atoms to be varied over a large range of the parameter space. We first calculate the entanglement by way of the von Neumann entropy and then examine the possibility of violating the CHSH inequality for finite temperatures and in the presence of experimental losses.

Coherent control of entanglement with atomic ensembles

K. S. Choi[1,*], A. Goban[1], S. B. Papp[1,†], S. J. van Enk[2], H. J. Kimble[1]

[1]*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Department of Physics, University of Oregon, Eugene, OR, USA*

Quantum networks are composed of quantum nodes which coherently interact by way of quantum channels. They offer powerful capabilities for quantum computation, communication, and metrology[1]. A generic requirement for these realizations is the capability to store and process quantum states among multiple quantum nodes, and to disseminate their resources throughout the network by way of quantum channels[1,2]. Here we describe a series of recent experiments[3−5] where single excitations in atomic ensembles are collectively coupled to optical modes, and provide efficient means for the coherent transfer of entangled states between matter and light[2].

We first report an experiment where entanglement between two atomic ensembles is created by reversible mapping of an entangled state of light[3]. First, a single photon is split into two modes to generate photonic entanglement. This entangled field state is then coherently mapped to an entangled matter state for two atomic ensembles by electromagnetically induced transparency. On demand, the stored entanglement is converted back into entangled field state. Unlike the original scheme[2], our approach is inherently deterministic, suffering principally from the finite EIT efficiencies, with the overall entanglement transfer into and out of the memories of 20%.

We have extend our work to multipartite quantum systems. In particular, we demonstrate measurement-induced entanglement for one excitation shared among four spatially distinct atomic ensembles[4]. Here, the entangled state for four atomic ensembles is created by the quantum interference in the measurement process. The entangled W-state of the four ensembles is then converted into four propagating beams of light, with full quadripartite entanglement confirmed by way of quantum uncertainty relations[5]. By monitoring the temporal decay of entanglement, we characterize the dissipative dynamics of multipartite entanglement for our system. When combined with the capability for coherent mapping of entangled photonic states to matter[3], our experiment constitutes an important tool for the distribution of multipartite entanglement across quantum networks.

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† Present address: Time and Frequency Division, NIST, Boulder, Colorado, USA

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* contact: kyung114@caltech.edu

Quantum Entanglement Between Optical Photon and Solid-state Spin Qubit

Y. Chu[1], E. Togan[1], A. Trifonov[1], L. Jiang[2], J. Maze[1], L. Childress[3], M. V. G Dutt[4], A. Sørensen[5], P. Hemmer[6], A. S. Zibrov[1], M. Lukin[1]

[1] *Harvard University, Cambridge, MA, USA*
[2] *California Institute of Technology, Pasadena, CA, USA*
[3] *Bates College, Lewiston, ME, USA*
[4] *University of Pittsburgh, Pittsburgh, PA, USA*
[5] *University of Copenhagen, Copenhagen, Denmark*
[6] *Texas A&M University, College Station, TX, USA*

Nonlocal quantum entanglement is among the most fascinating aspects of quantum theory. Motivated by the potential realization of quantum networks that require entanglement of remote quantum nodes with long-term quantum memory, we demonstrate nonlocal entanglement between a single optical photon and a solid-state qubit associated with the single electronic spin of a Nitrogen Vacancy impurity in diamond. Our experiments demonstrate a high degree of control over solid-state qubits in the optical domain and provide a fundamental building block for the realization of quantum optical networks based on long-lived electronic and nuclear spin memory in the solid-state.

Nonlinear Faraday Rotation in Cold Atoms for Quantum Information and Magnetometry

A. Wojciechowski[1,3], E. Corsini[2,3], J. Zachorowski[1,3] W. Gawlik[1,3]

[1]*Institute of Physics, Jagiellonian University, Reymonta 4, PL-30-059 Kraków, Poland*
[2]*Department of Physics, University of California, Berkeley, CA 94720-7300, USA*
[3]*Joint Kraków-Berkeley Atomic Physics and Photonics Laboratory*

We report[1] on the first observation of Nonlinear Faraday Rotation (NFR) with cold atoms prepared in a magneto-optical trap (MOT) at $\simeq 100\ \mu$K temperature. The nonlinearity of rotation results from a long-lived coherence of ground-state Zeeman sublevels[2], which makes NFR a candidate for the study and detection of qubits.

NFR with cold atoms, with a Doppler width narrower than the natural linewidth, makes it possible to address a single hyperfine transition and to create a quantum superposition state in a well controlled way; which distinguishes this situation from experiments done with Alkali vapor cells at room temperature. In the experiment we formed a coherence between Zeeman sublevels of the $5^2S_{1/2}$ F = 3 state of ^{85}Rb and we observed NFR resonances, (Fig.1-left) with a width of 30 mG and up to 6° in amplitude (a Verdet constant $\simeq 3 \times 10^5$deg/G.m). For high field magnetometry applications we used the AMOR modulation technique[3] and performed measurements of magnetic fields up to 9 G. The narrow resonance, spatial confinement, and time resolved observation, allows the measure of a wide range of transient and static magnetic fields with 10 μs time resolution, sub-mm spatial resolution, and sub-mG sensitivity within the volume occupied by the cold atom cloud. In addition we studied the time evolution of specific ground-state Zeeman coherences with Δm = 2 at various light intensities (Fig.1-right), which opens up a path to a better understanding and control of long-lived atomic coherences which are vital to fundamental atomic physics, quantum information, and magnetometry.

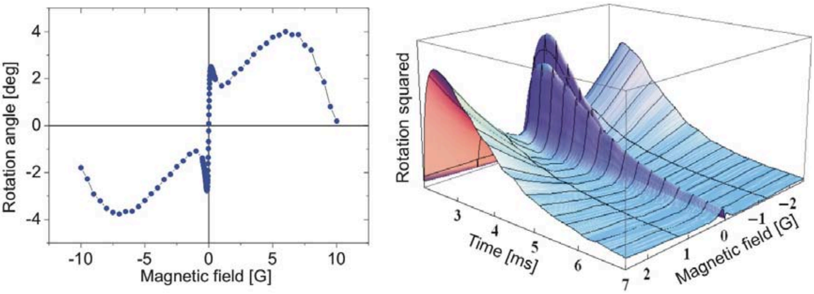

Figure 1: *Left: Linear (wide) and nonlinear (narrow) Faraday rotation resonances. Right: Time resolved NFR signal related to the Δm = 2 coherence for a 64 μW probe beam intensity.*

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Quantum Sampling Using Schrödinger's Equation

A. Denney[2], C. Moore[1,2,3]

[1] *CQuIC, Department of Computer Science, University of New Mexico, Albuquerque, New Mexico, United States of America*
[2] *CQuIC, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, United States of America*
[3] *Santa Fe Institute, Santa Fe, New Mexico, United States of America*

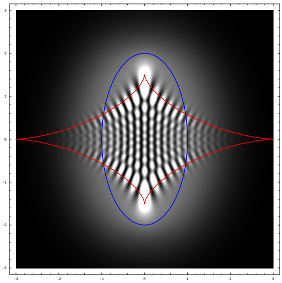

Figure 1: *An initial wavefunction concentrated near an ellipse (blue) evolved to have high concentration near its evolute, a stretched astroid known as a Lamé curve (red).*

Inspired by recent work in continuous time quantum walks[1] [2] [3] in combination with the well-known analogy between quantum walks and evolution under the Schrödinger equation, we show how to efficiently sample from the "evolute" of a plane-curve – its set of centers of curvature. Constructive interference occurs most strongly here. We analyze the intensity of this concentration, and how tightly the width in which this concentration happen in terms of (fractional) powers of a scaled time parameter τ. Although this analysis is of the Schrödinger equation, this is primarily a geometric effect, and similar results have been measured with standard optical diffraction.[4] In higher dimensions, not as much constructive interference is guaranteed as a surface may curve in multiple ways. However, for n-spheres, the high degree of symmetry allows us to efficiently sample points near the center, with Prob $\propto \epsilon$ of being within ϵ of the center. This is a huge improvement over sampling from a solid ball, where Prob $\propto \epsilon^n$. In contrast, for the analagous classical setting, where we can sample from the surface of a sphere, it requires $\theta(n)$ samples to determine the center to any degree of accuracy.

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Criteria for spin EPR entanglement and Bell nonlocality

Q. Y. He, P. D. Drummond, M. D. Reid

ACQAO, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

To quantify entanglement in ultra-cold atomic systems, it is essential to develop signatures that do not require local oscillators and quadrature measurements. Here we develop a number of novel, spin-based measures of entanglement, EPR and Bell nonlocality. These are measurable using micro-wave Rabi rotations and optical absorption.

To deduce entanglement between two separated locations in the EPR sense, we use CFRD inequalities[1] to derive spin EPR and Bell nonlocality criteria. In particular, if

$$|\langle J_+^A J_-^B ...\rangle|^2 > \langle\langle J_\pm^A J_\mp^A J_\pm^B J_\mp^B ...\rangle$$

($J_\pm^{A/B}$ are the spin raising and lowering operators), we can prove entanglement between the sites A and B. There is a violation of a Bell inequality if the moments satisfy

$$|\langle J_+^A J_-^B ...\rangle|^2 > \langle[(J^A)^2 - (J_z^A)^2][(J^B)^2 - (J_z^B)^2]....\rangle$$

and are measured via simultaneous measurements at spatially separated sites. These criteria are predicted to be violated by different types of squeezed bosonic states. For example we might prepare coupled modes a_+ and b_+ by placing one in a Fock number state $|N_0\rangle$ and the other in a vacuum $|0\rangle$ and coupling via a "beam splitter-type" interaction. The coupled modes can be written

$$|\Psi\rangle = \sum_{n=0}^{N_0} c_n |n\rangle_{a_+} |N_0 - n\rangle_{b_+}$$

where

$$c_n = \frac{\sqrt{N!}}{\sqrt{2^N}\sqrt{n!}\sqrt{(N-n)!}}$$

Then $\langle a_+^\dagger a_+\rangle = \langle b_+^\dagger b_+\rangle = \langle a_+^\dagger b_+\rangle = N/2$ and $\langle a_+^\dagger a_+ b_+^\dagger b_+\rangle = N(N-1)/4$. We suppose a second pair of modes a_- and b_- are similarly prepared with same correlation, but are independent of the modes a_+ and b_+. We can evaluate the entanglement criterion using $J_+^A = a_+^\dagger a_-$ and $J_-^A = a_+ a_-^\dagger$ and $J_+^B = b_+^\dagger b_-$ and $J_-^B = b_+ b_-^\dagger$, and deduce the entanglement between the modes.

Importantly, we can directly deduce from the depth of EPR entanglement, the minimum number of particles that are involved in the EPR entangled state.

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EPR entanglement in a four-mode BEC

M. D. Reid, Q. Y. He, P. D. Drummond

ACQAO, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

Einstein, Podolsky and Rosen (EPR), in their famous 1935 paper, demonstrated the incompatibility between the premises of *local realism* and the completeness of quantum mechanics. The original EPR paper used continuous position and momentum variables, and relied on their commutation relations, via the corresponding uncertainty principle.

Entanglement is the basis of the EPR paradox, and has potential applications in sub-shot noise interferometry and ultra-sensitive detection. It can be generated by the interference of two squeezed states on a 50:50 beamsplitter. This has already been achieved in optical experiments [1]. Bose Einstein condensates (BEC) of ultracold atoms are also considered good candidates to provide entangled states involving a large number of particles. These have potential both for new tests of quantum mechanics, and for ultra-sensitive magnetometers or gravimeters. Recently, several experimental groups have observed spin-squeezed states in a BEC of ^{87}Rb atoms[2]. This has been used to demonstrate atomic interferometry beyond the shot-noise limit.

Here we consider four-mode interferometry involving two spin orientations in each of two separated potential wells. We show that with more than one mode or spin orientation at each location, EPR entanglement is detectable via spin measurements. The entanglement witnesses used are either spin versions of the Heisenberg-product entanglement criterion, or recently developed non-Hermitian operator product inequalities. These are closely related to entanglement techniques developed in fiber optics.

In the simplest case, we can show entanglement between the two wells, just from number correlations, using the Hillery-Zubairy non-Hermitian operator product criterion. This is simplest to demonstrate experimentally. In effect, one simply has to combine existing number correlation measurement techniques with a measurement of total number fluctuations. This is more powerful than the spin-squeezing criterion as it clearly demonstrates entanglement between the spatially separated two modes. However, without atomic local oscillators, this technique requires a phase-sensitive recombination measurement of particles from the two wells. In other words, this criterion is not readily obtainable with spatially separated measurements.

A second type of entanglement again uses the Hillery-Zubairy criterion, except applied to spin operators, which can be measured in each well. Technically this requires the two pairs of modes to be decoupled, which is achievable using a four spatial-mode type of experiment, similar to recent atom-chip experimental approaches. Finally, a third proposal uses dynamical evolution in a double-well, double-spin arrangement at a Feshbach resonance. This results in correlated spin EPR type entanglement.

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Entanglement of Two Individual ^{87}Rb Atoms Using the Rydberg Blockade

C. Evellin, T. Wilk, A. Gaëtan, A. Browaeys, P. Grangier

Laboratoire Charles Fabry de l'Institut d'Optique, Palaiseau, France

Entanglement between several particles has been proven to be useful[1] for quantum computation. As entanglement can be generated through interactions between particles, the use of neutral atoms interacting through a highly excited Rydberg state seems promising. Indeed, the interactions can be switched on and off at will and can act at long distances (few μm). In our experiment we aim at producing deterministically an entangled state between two ^{87}Rb atoms in their hyperfine ground states, using the Rydberg blockade mechanism[2].

In this experiment we focus a 810 nm laser beam using a microscope objective of high numerical aperture to create an optical tweezer that traps only one atom[3]. The qubit is encoded in the $|0\rangle = |5s_{1/2}, F = 1, m_F = 1\rangle$ state and the $|1\rangle = |5s_{1/2}, F = 2, m_F = 2\rangle$ state. It can be controlled with two Raman lasers with a very high efficiency (π pulse is 99% efficient). A second atom can easily be implemented by sending an additionnal 810 nm laser beam through the microscope objective with a slight angle relative to the first one. The two atoms are separated by 4 μm and can be controlled individually.

The entanglement scheme works as follows: The ground state $|1\rangle$ of the atoms is coupled to the Rydberg state $|r\rangle = |58d_{3/2}, F = 3, m_F = 3\rangle$ by a two-photon transition using a π-polarized 795 nm laser (close to the D1-line of Rb) and a second σ^+ -polarized 475 nm laser. Due to the large dipole-dipole interaction, the doubly excited state $|rr\rangle$ is shifted by about 50 MHz, and lasers that excite a single atom into the Rydberg state cannot excite both atoms at the same time. In the resulting state[4] only one of the two atoms is excited in the Rydberg state. The Rydberg state is then mapped down to the qubit state: $|r\rangle \rightarrow |0\rangle$ using a two-photon transition with the same 475 nm laser and a σ^+ -polarized 795 nm laser. The amount of entanglement obtained by this scheme is quantified using the fidelity F with respect to the target $|\psi^+\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right)$ Bell state. In our case, 39% of trials end up with the loss of at least one atom. If we dismiss those cases and keep trials where both atoms are still trapped, the entanglement between the atoms has a fidelity of $F = 0.75$.

We are now working on characterizing the lifetime of the entangled state. We are also implementing a third optical tweezer to study the effect of geometry on the Rydberg blockade strength, and to study the entanglement of three atoms. The status of the experiment will be reported.

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Interacting cavities: Single photon opto-mechanics and a set of two coupled opto-mechanical systems

Uzma Akram, G.J. Milburn

Department of Physics, School of Mathematics and Physics, The University of Queensland, St Lucia QLD 4072, Australia.

An example of an opto-mechanical system constitutes a cavity with a movable mirror. The cavity provides a radiation pressure force on the moving mirror subject to a linear restoring force, forming a mechanical resonator[1].

Firstly we study a coherently driven opto-mechanical system cascaded to a cavity modeled as a single photon source. We show that the probability for the additional photon to be emitted by the opto-mechanical cavity will exhibit oscillations under a Lorentzian envelope, when the driven interaction with the mechanical resonator is strong enough.

Next, we study two separate coherently driven opto-mechanical cavities coupled to each other. In this setting, we consider photons exchanged both reversibly and irreversibly between the two cavities. Each opto-mechanical cavity is described in terms of a linearised interaction in the cavity field operators by expanding around the coherent steady state field in the cavity[2]. Here we find for particular parameters, photon-phonon entanglement exists in the setup.

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Coherent Blue Light Generation in Rb Vapour

A.M. Akulshin, A.A. Orel, K. Fenech, R.J. McLean, P. Hannaford

Swinburne University of Technology, Hawthorn, Victoria, Australia

Low-intensity nonlinearity of atomic media associated with light-induced atomic coherence may result in the generation of new optical fields with substantial frequency up-conversion [1].

We have studied frequency up-conversion of near-IR resonant laser radiation in Rb vapour. After excitation to the $5D_{5/2}$ level by co-propagating laser beams at 780 nm and 776 nm, Rb atoms decay to the $6P_{3/2}$ level and then to the ground state, emitting photons at 420 nm. At sufficiently high atomic density and laser intensity narrow-linewidth blue light with low divergence appears as a result of wave mixing of the laser fields with the third field at 5.2 μm produced by stimulated emission from the $5D_{5/2} - 6P_{3/2}$ transition. We find that the direction of the coherent blue light (CBL) agrees with the phase-matching relation, determined by the wave vectors of all the optical fields and the refractive index they see. The direction along which optimal phase matching condition is achieved forms a light-induced waveguide for CBL generation.

The spatial and spectral properties of the blue light are very sensitive to various parameters, such as the frequency detuning, the polarization of the applied laser fields and their spatial overlap [2]. We have also studied the effect of optical pumping on CBL. Velocity selective optical pumping produced by a laser tuned on the D1 line may decrease the atomic density threshold of CBL generation, enhance the CBL intensity, as shown in Fig. 1(a,b), and affect the transverse spatial distribution of the blue beam. Figure 1c shows (i) CBL temporal response to a sharp-edge optical pumping pulse (ii). Velocity selective depopulation produced on the D1 line may also decrease the CBL intensity. Thus, optical pumping allows efficient control of CBL.

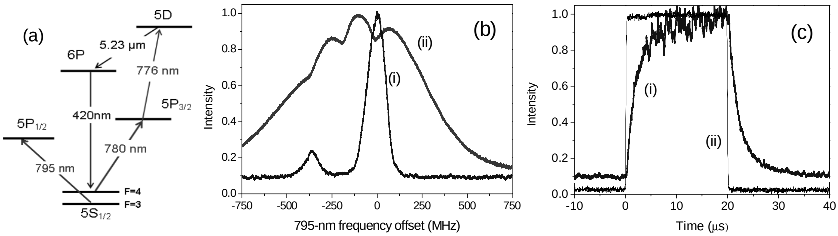

Figure 1: *(a) Energy level scheme; (b) Blue light intensity as a function of the pump laser detuning; (c) Temporal blue light intensity evolution with pulsed optical pumping.*

Possible schemes for the generation of ultraviolet and THz radiation, as well as the correlation of optical fields from different spectral regions using this approach, will be discussed.

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Four-wave mixing as a sub-kHz probe for ground-state atomic coherence

A.M. Akulshin, P. Hannaford

Swinburne University of Technology, Hawthorn, Victoria, Australia

Potential applications in quantum information storage and processing as well as fundamental aspects of atom-light interaction generate widespread attention to coherent atomic media. Careful accounting of long-lived atomic coherence is crucial for a proper explanation of a variety of nonlinear processes occurring in atomic media at low light intensity [1]. On the other hand, nonlinear processes could be used as an effective probe for testing coherent atomic states.

We demonstrate that wave mixing can be used for distinguishing different coherent mechanisms responsible for the enhanced Kerr nonlinearity in Rb vapour. Two mutually coherent, co-propagating resonant optical waves with sub-MHz frequency detuning produce new coherent waves, which are analyzed using an RF heterodyne method. Figure 1 shows the beating of the new optical wave generated by the mixing process and the off-resonant reference for different transitions on the Rb D1 line. The largest observed signal is on the transition *F=3-F'=2*, where ground-state population is trapped in an EIT-type coherent superposition. The absence of beating on the open transition *F=2-F'=3*, where a coherent dark state does not exist, suggests that there is no EIA-type coherence either, while for parallel polarizations the signal occurs due to coherent population oscillations.

Thus, this experiment enable one to distinguish between conventional and anomalous electromagnetically induced absorption (EIA). Anomalous EIA has been recently explained by quantum interference among competing two-photon transitions [2].

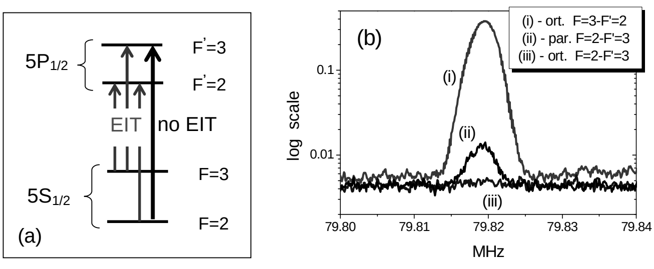

Figure 1: *(a) Energy level scheme of the Rb D1 line; (b) Beat signals for different polarizations and optical transitions.*

High signal-to-noise ratio and spectral resolution within the laser linewidth demonstrate the rich potential this approach offers for understanding the processes involved in enhancing low-intensity atomic nonlinearities.

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Propagation of pulsed thermal light in Rb atomic vapor

I. H. Bae[1], Y. -W. Cho[2], H. J. Lee[1], Y. -H. Kim[2], H. S. Moon[1]

[1]*Department of Physics, Pusan National University, Busan, 609-735, Korea*
[2]*Department of Physics, Pohang University of Science and Technology, Pohang, 790-784, Korea*

We report an experimental demonstration of slow and superluminal propagation of chaotic thermal light in the Λ-type system of the $5S_{1/2}$-$5P_{1/2}$ transition of ^{87}Rb atom. Figure 1 shows electromagnetically induced transparency (EIT) and enhanced absorption (EA) spectrums where the coupling field takes the form of a standing wave, respectively. The slowed propagation of pulsed thermal light was demonstrated in an electromagnetically induced transparency (EIT) while the superluminal propagation was demonstrated with the enhanced absorption (EA). We have also demonstrated that the photon number statistics of the thermal light is preserved for both the subluminal and superluminal cases[1]. These results suggest that it should be possible to control the speed of the probe pulse from subluminal to superluminal continuously while maintaining the statistical properties of the light pulse.

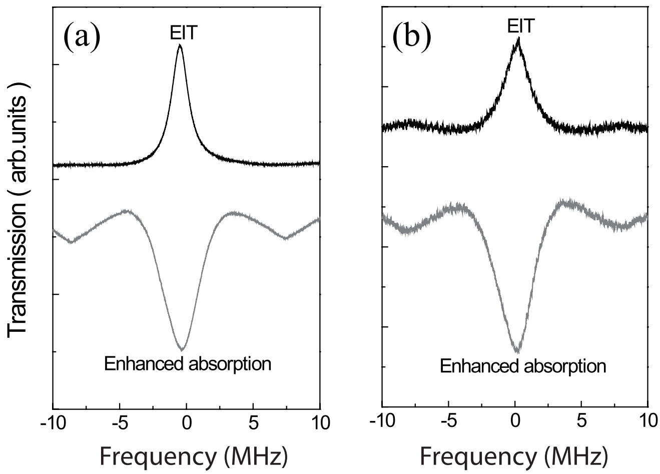

Figure 1: *The measured EIT and EA transmission spectra for the laser probe, (a), and the thermal light probe, (b), as a function of probe frequency.*

[1]I. H. Bae, Y. -W. Cho, H. J. Lee , Y. -H. Kim and H. S. Moon, "Superluminal propagation of pulsed thermal light in atomic vapor" to be submitted on Optics express.

Cold atoms and QND measurements in an optical cavity

A. Bertoldi[1], S. Bernon[1], T. Vanderbruggen[1], R. Kohlhaas[1], A. Landragin[2], P. Bouyer[1]

[1]*Institut d'Optique, CNRS and Univ. Paris-Sud, F-91127 Palaiseau, France*
[2]*LNE-SYRTE, Observatoire de Paris, CNRS and UPMC, F-75014 Paris, France*

We report on the trapping of ^{87}Rb atoms in a ring folded cavity pumped with a fiber laser at 1560 nm. The optical potential generated in the cavity was characterized with a tomographic technique on the light-shift induced potential. By using phase masks to optimise the coupling efficiency, we locked the laser to different transversal modes of the non-degenerate cavity, obtaining a scalable multi-well system. We aim to obtain Bose-condensation in the cavity by lowering the depth of the optical potential to force evaporative cooling.

We also developed a heterodyne detection scheme to non-destructively probe the atomic ensemble on the D_2 line. A weak, close to resonance probe beam acquires an atomic induced dephasing when passing through an atomic cloud. This phase encodes information on the atom number or number difference depending on the probe frequency, and can be measured by optically beating the probe with a strong, far from resonance reference beam. In a first prof-of-principle experiment the detection tool was tested in free space on atoms released from a MOT; the position of the state vector on the Bloch sphere was continuously measured during an interferometric sequence. We want to obtain spin squeezing and apply the scheme on optically trapped atoms. Using a probe beam injected in the cavity is possible to improve the measurement SNR by the square root of the cavity finesse.

Polaritons and Pairing Phenomena in Bose–Hubbard Mixtures

M. J. Bhaseen[1], M. Hohenadler[1,2], A. O. Silver[1], B. D. Simons[1]

[1] *University of Cambridge, Cavendish Laboratory, Cambridge, UK.*
[2] *Institute of Theoretical Physics and Astrophysics, University of Würzburg, Germany.*

Motivated by recent experiments on cold atomic gases in ultra high finesse optical cavities, we consider the problem of a two-band Bose–Hubbard model coupled to quantum light. Photoexcitation promotes carriers between the bands and we study the non-trivial interplay between Mott insulating behavior and superfluidity. The model displays a global U(1) X U(1) symmetry which supports the coexistence of Mott insulating and superfluid phases, and yields a rich phase diagram with multicritical points. This symmetry property is shared by several other problems of current experimental interest, including two-component Bose gases in optical lattices, and the bosonic BEC-BCS crossover problem for atom-molecule mixtures induced by a Feshbach resonance. We corroborate our findings by numerical simulations. [1,2]

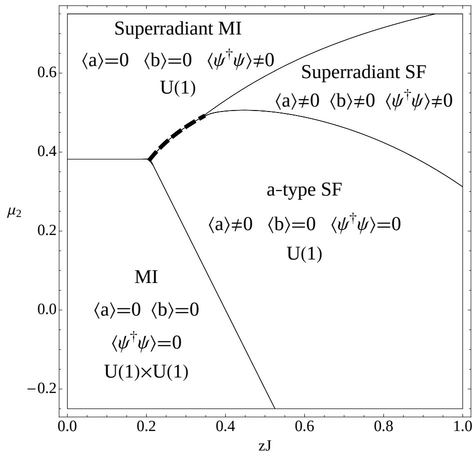

Figure 1: *Mean field phase diagram of the two-component Bose–Hubbard model coupled to quantum light. This includes a superradiant Mott insulator supporting a condensate of photoexcitations.*[1,2]

[1] M. J. Bhaseen, M. Hohenadler, A. O. Silver, B. D. Simons, *Polaritons and Pairing Phenomena in Bose–Hubbard Mixtures*, Phys. Rev. Lett. **102**, 135301 (2009).

[2] A. O. Silver, M. Hohenadler, M. J. Bhaseen, B. D. Simons, *Bose–Hubbard Models Coupled to Cavity Light Fields*, Phys. Rev. A **81**, 023617 (2010).

Collective Dynamics of Bose–Einstein Condensates in Optical Cavities

J. Keeling, M. J. Bhaseen, B. D. Simons

University of Cambridge, Cavendish Laboratory, Cambridge, UK.

Recent experiments on Bose–Einstein condensates in optical cavities have reported a quantum phase transition to a coherent state of the matter-light system – superradiance.[1] The time dependent nature of these experiments demands consideration of collective dynamics. Here we establish a rich phase diagram, accessible by quench experiments, with distinct regimes of dynamics separated by non-equilibrium phase transitions.[2] We include the key effects of cavity leakage and the back-reaction of the cavity field on the condensate. Proximity to some of these phase boundaries results in critical slowing down of the decay of many-body oscillations. Notably, this slow decay can be assisted by large cavity losses. Predictions include the frequency of collective oscillations, a variety of multi-phase co-existence regions, and persistent optomechanical oscillations described by a damped driven pendulum. These findings open new directions to study collective dynamics and non-equilibrium phase transitions in matter-light systems.

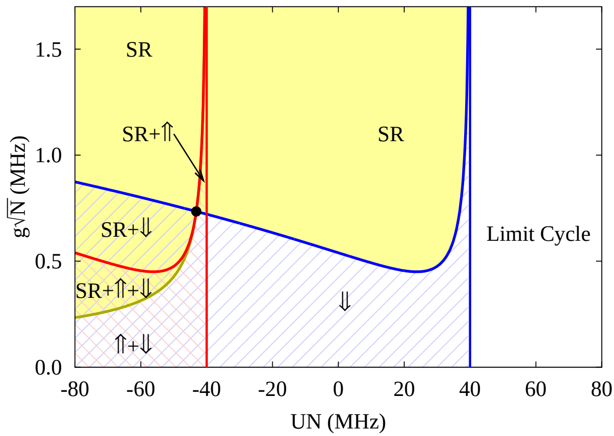

Figure 1: *Dynamical phase diagram showing the steady states of the Dicke model with co-rotating and counter-rotating terms set equal, $g = g'$, and parameters $\omega = 20\text{MHz}$, $\omega_0 = 0.05\text{MHz}$, and $\kappa = 8.1\text{MHz}$ taken from Ref. 1. We include the back-reaction, U, of the cavity light field on the condensate with N atoms.*[1,2]

[1] K. Baumann, C. Guerlin, F. Brennecke, T. Esslinger, *The Dicke Quantum Phase Transition in a Superfluid Gas Coupled to an Optical Cavity*, Nature, **464**, 1301 (2010).

[2] J. Keeling, M. J. Bhaseen, B. D. Simons, *Collective Dynamics of Bose–Einstein Condensates in Optical Cavities*, `arXiv:1002.3108`.

Photonic Bus for Trapped Ions

M. Cetina[1], M. Scholz[1], A. Bylinskii[1], A. Grier[1], F. Oručevič[2], Y. Ge[1], I. Chuang[1] and V. Vuletič[1]

[1]*MIT-Harvard Center for Ultracold Atoms, Cambridge, MA, USA*
[2]*University of Sussex, Brighton, UK*

We report progress towards interfacing individually addressable atomic ions with photons using an optical resonator. We load Yb^+ ions into a linear array of Paul traps spaced by 160μm and located 140-160μm above the surface of a lithographic gold-on-quartz chip. The traps are overlapped with the axis of an optical cavity resonant with the $^2S_{1/2} -^2 P_{1/2}$ transition in Yb^+. Maximal single-ion cooperativity of 0.09, large number of ions strongly confined in the Lamb-Dicke regime and the availability of magnetic-field insensitive Yb^+ ground hyperfine states make our system attractive for long-term photon storage. Single-ion addressability allows separated general-purpose few-ion quantum registers to be operated and entangled by photons emitted into the optical resonator.

Electromagnetically Induced Transparency Based Cross-Phase Modulation at Atto-Joule Levels

H.-Y. Lo, Y.-C. Chen, P.-C. Su, H.-C. Chen, J.-X. Chen, Y.-F. Chen

Department of Physics, National Cheng Kung University, Tainan 701, Taiwan

All-optical control of light using electromagnetically induced transparency (EIT) [1], such as the photon switching and the cross-phase modulation (XPM), has attracted great attention over the past decade. Here we report the first experimental demonstration of the EIT-based XPM at few-hundred-photon levels. A phase shift of 0.005 rad of a probe pulse modulated by a signal pulse with an energy of 100 attojoule, or equivalent to $\sim$ 400 photons, is observed. The experimental result shows a phase shift of a single-photon pulse controlled by another is $\sim 1 \times 10^{-5}$ rad, which is in excellent agreement with the theoretical prediction [2]. The discrepancy between the experimental data and the theoretical maximum phase shift at the single-photon level is discussed. This work offers exciting prospects for few-photon applications in quantum information science.

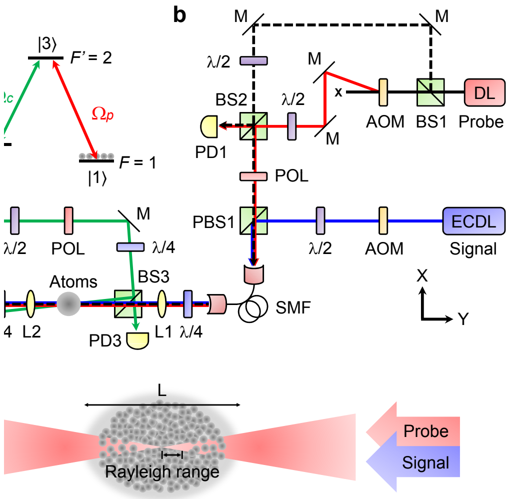

Figure 1: ***Experimental apparatus. a**, Energy levels of* ^{87}Rb *D_2-line transition for the EIT-based XPM experiment. Signal detuning is defined as $\Delta_s = \omega_s - \omega_{24}$, where ω_s and ω_{24} are the frequencies of the signal field and the $|2\rangle \leftrightarrow |4\rangle$ transition, respectively. **b**, ECDL, external-cavity diode laser; DL, diode laser; PBS, polarizing beam splitter; BS, beam splitter; AOM, acousto-optic modulator; λ/2, half-wave plate; λ/4, quarter-wave plate; POL, polarizer; SMF, single-mode fibre, PD, photodetector; P, pinhole; L, lens. **c**, Schematic diagram of the probe and signal fields focused into the cold atoms.*

[1] S. E. Harris, "Electromagnetically induced transparency", *Phys. Today* **50**, 36-42 (1997).
[2] S. E. Harris & L. V. Hau, "Nonlinear optics at low light levels", *Phys. Rev. Lett.* **82**, 4611-4614 (1999).

Near field effects in superconducting atom chips

R. Fermani[1,2], T. Müller[1,2], B. Zhang[2], M.J. Lim[2,3], R. Dumke[2]

[1]*Centre for Quantum Technologies, National University of Singapore, Singapore*
[2]*Nanyang Technological University, Division of Physics, Singapore*
[3]*Department of Physics and Astronomy, Rowan University, New Jersey, USA*

In the area of magnetic trapping of ultracold atoms, considerable attention has been recently devoted to the interaction of atomic clouds with the surfaces of both superconducting atom chips and superconducting solid state devices. Technological advances in this area will lead to a new generation of fundamental experiments leading to the control of the interface between atomic systems and quantum solid state devices. The implementation of such technologies depends on the ability to control and efficiently manipulate atoms close to superconducting surfaces. However, below a certain separation the atom-surface coupling is strong enough that the trapping potential is modified by the interaction of the atomic magnetic moment with the near-field magnetic noise. This leads to level shift due to Casimir-Polder potential, atom heating and spin flip induced atomic loss. The electromagnetic field noise is significantly smaller in the vicinity of a superconductor, however for the small distances involved, near field noise can still represent a limitation.

Our investigation focuses on the heating mechanism, the thermally-induced spin flip and the Casimir-Polder potential experienced by an atom held close to two different superconductors [1] [2] [3] [4] [5]. We consider niobium (a conventional s-wave superconductor) and YBCO or BSSCO (both high temperature d–wave superconductors). The presented results are of interest for future development of technologies involving superconducting atom chips. Moreover, they represent an important step towards the adoption of neutral atoms as sensitive probes in the study of properties of different types of superconductors.

[1]R. Fermani, T. Müller, B. Zhang, M.J. Lim, and R. Dumke, J. Phys. B: At. Mol. Opt. Phys. **43**, 095002 (2010).

[2]R. Fermani, and S. Scheel, J. Phys. B: At. Mol. Opt. Phys. **43**, 025001 (2010).

[3]T. Müller, B. Zhang, R. Fermani, K.S. Chan, Z.W. Wang, C.B. Zhang, M.J. Lim, and R. Dumke, New J. Phys. **12**, 043016 (2010).

[4]T. Müller, B. Zhang, R. Fermani, K.S. Chan, M.J. Lim, and R. Dumke, Phys. Rev. A **81**, 053624 (2010).

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Electromagnetically induced transparency with single atoms in a cavity

E. Figueroa[1], M. Mücke[1], J. Bochmann[1] C. Hahn[1] K. Murr[1] S. Ritter[1] C. J. Villas-Boas[1,2] G. Rempe[1]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany*

[2]*Departamento de Fisica, Universidade Federal de São Carlos, 13565-905 São Carlos, SP, Brazil*

Optical nonlinearities offer unique possibilities for the control of light with light. Performing such experiments in the quantum domain with one, or just a few particles of both light and matter will allow the implementation of quantum computing protocols with atoms and photons. Reaching these limits is challenging and requires a strong matter-light interaction as provided by cavity quantum electrodynamics (QED). In this work we measure EIT with a single ^{87}Rb atom trapped inside a high-finesse optical cavity. The atom acts as a quantum-optical transistor with the ability to coherently control the transmission of light through the cavity. We also investigate the scaling of EIT when the atom number is increased one by one [1]. Incorporating EIT will increase the capabilities of cavity QED from the production of single photons towards the coherent manipulation of propagating quantum light fields. For a system with many individually addressable atoms, this will ultimately lead to the realization of a quantum network, where the generation, propagation and absorption of light is coherently controlled at the quantum level. Merging the ability to perform EIT experiments with a controlled number of atoms together with light storage, a highly nonlinear beam splitter could be realized that subtracts a well-defined number of photons from a coherent input field. In future experiments we also plan to go beyond the coherent manipulation of the average light intensity and investigate the possibility to also control the photon statistics. This could bring ideas like that of an EIT-controlled photon blockade in an atomic four-level system into reality.

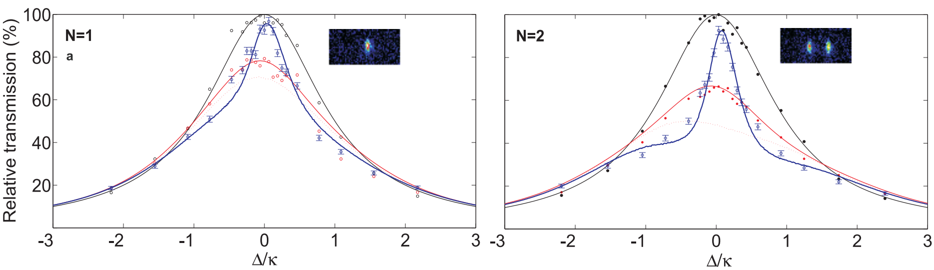

Figure 1: ***Cavity EIT spectra for atoms by the number.*** *Empty cavity transmission (black data and curve), Two-level QED situation (red data and curve) and cavity EIT scenario (blue data and curve) for exactly one and two atoms. The probe field detuning is normalized to the cavity decay.*

[1]This work recently appeared in the Nature advance online publication system: doi:10.1038/nature09093

Spinor slow-light polaritons and random-mass Dirac model

Michael Fleischhauer[1], Johannes Otterbach[1], Razmik Unanyan[1], Gediminas Juzeliunas[2], Julius Ruseckas[2]

[1] *Fachbereich Physik und Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*
[2] *Institute of Theoretical Physics and Astronomy, Vilnius University, 01108 Vilnius, Lithuania*

Recently there has been a growing interest in systems with an effective Dirac dynamics. We here show that an effective Dirac-like dynamics also emerges for two-component, i.e. spinor-like, slow-light polaritons [1] in 1D. They possess a controllable effective speed, corresponding to the very small group velocity in media exhibiting electromagnetically induced transparency (EIT). This allows experimental studies of a number of interesting effects of relativistic dynamics at laboratory energy and length scales. Additionally the effective mass, determined by laser detuning, is adjustable including the sign, which provides access to interesting phenomena such as the unusual localization in the random-mass Dirac model [2].

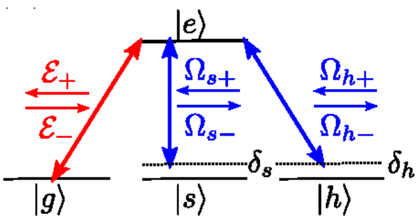

Figure 1: *Linkage pattern with two counter-propagating control fields $\Omega_\pm$ to create a stationary pattern of counter-propagating probe light $\mathcal{E}_\pm$ described by a Dirac equation with effective speed of light $c^* = v_{\rm gr}$ and effective mass $m^* = \hbar\delta/k_p$ ($\delta = \delta_h = -\delta_p$).*

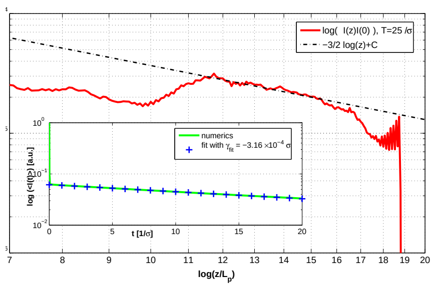

Figure 2: *Intensity correlation of localized stationary-light polariton from numerical simulation of Maxwell Bloch equations corresponding to Dirac-like spinor polaritons with random mass. Insert shows small decay due to non-adiabatic losses.*

[1] M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. **77**, 633 (2005)
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[3] R.G.Unanyan et al. *Spinor Slow-Light and Dirac particles with variable mass* arXiv:1005.3429, 2010

Photonic quantum simulators

Dimitris G. Angelakis[1,2]

[1]*Science Department, Technical University of Crete, Chania, Crete, Greece, 73100*
[2]*Centre for Quantum Technologies, National University of Singapore, 2 Science Drive 3, Singapore 117542*

I will start by describing the basic motivation for using systems of photons interacting with atoms in cavities and fibers to simulate condensed matter phenomena. I will proceed by briefly reviewing our various results on simulations of Mott to superfluid phase transitions in coupled cavities doped with two level systems[1], the applications in measurement based quantum computation, in simulations of effective spin models[2], and of the Fractional Quantum Hall effect[3].
In the second part of the talk I will describe in more detail our recent schemes in generating mutli-component polaritonic Luttinger Liquids in fibers where the chance of observing spin charge separation with light is possible.[4]

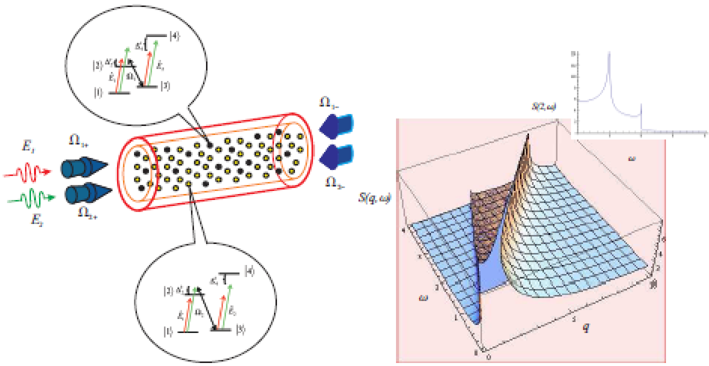

Figure 1: *Quasiparticles formed from light-matter excitations (polaritons) in a fiber are shown to obey the Lieb Liniger dynamics of a two-component quantum liquid. Efficient observation of effective spin-charge separation is possible.*

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[3]J. Cho, D. G. Angelakis, S. Bose, Fractional Quantum Hall state in coupled cavities. Phys. Rev. Lett. 101, 246809 (2008)

[4]D.G. Angelakis, M. Huo, E. Kyoseva LC Kwek Simulating spin and charge using light, arXiv:1006.xxxx

Anderson localization with ultracold atoms: from the 1D direct observation to the quantum simulation of the 3D transition

A. Bernard, F. Jendrzejewski, S. Seidel, P. Cheinet, V. Josse, P. Bouyer, A. Aspect

Laboratoire Charles Fabry de l'Institut d'Optique, Campus Polytechnique RD128, 91127 Palaiseau, France

One of the main challenges of modern condensed matter physics is the understanding of the electronic quantum transport in a disordered medium at the mesoscopic scale. There, interferences originating from coherent random scattering can lead to suppression of transport; this is the so-called Anderson localization[1]. Despite huge experimental efforts, many important questions remain, such as the accurate value of the critical exponents of the Anderson metal-insulator phase transition, or the effects of interactions. For these studies, ultracold atomic systems reveal themselves a very adapted tool to mimic the phenomenon with higher control and tenability[2]. Two years ago, we demonstrated the possibility to observe directly Anderson localization of 1D matterwaves[3], in an optically created correlated disorder. In this geometry, even though all states should be localized, the monotony of the phenomenon is broken in correlated disorder with the appearance of effective mobility edges. This involves a crossover between different steady states, which has been experimentally observed. This experiment paved the way for further studies: localization of interacting 1D matterwaves have been realized recently[45] and our group is now focusing on the higher dimension cases[6]. In my poster, I will give you the key features and the most recent progresses of the experiment we are now carrying out, which aims to observe directly the Anderson transition expected in the 3D geometry. As the dynamic of localization is expected to be very slow, we have implemented a magnetic levitation system that might allow us to observe time of flights of several seconds. I will also show you that the experiment requires large numerical apertures to be performed, since the design of the disordered potential is much more critical than for the 1D case.

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[3] J. Billy, V. Josse, Z. Zuo, A. Bernard, B. Hambrecht, P. Lugan, D. Clment, L. Sanchez-Palencia, P. Bouyer, A. Aspect, "Direct Observation of Anderson localization of matter-waves in a controlled disorder", Nature 453, 891 (2008)

[4] B. Deissler, M. Zaccanti, G. Roati, C. D'Errico, M. Fattori, M. Modugno, G. Modugno, M. Inguscio, "Delocalization of a disordered bosonic system by repulsive interactions", Nat. Phys., 6, 354 (2010)

[5] D. Dries, S.E. Pollack, J.M. Hitchcock, R.G. Hulet, "Dissipative Transport of a Bose-Einstein Condensate", arXiv, 1004:1891v1 (2010)

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Predicted mobility edges in one-dimensional incommensurate optical lattices

J. Biddle, S. Das Sarma

Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA

Localization properties of non-interacting quantum particles in one-dimensional incommensurate lattices are investigated with an short-range exponential hopping model that extends the nearest-neighbor tight-binding model. Energy dependent mobility edges are analytically predicted in this model and verified with numerical calculations. The results are then mapped to the continuum Schrödinger equation, and an approximate analytical expression for the localization phase diagram and the energy dependent mobility edges in the ground band is obtained.

Ion Trapping of the Third Kind

M. Enderlein, Ch. Schneider, T. Huber, S. Duewel, T. Schätz

Max-Planck-Institut für Quantenoptik, Garching, Germany

For the first time we demonstrate trapping of an ion in an optical dipole trap[1]. This comes after more than 60 years of ion trapping in Paul and Penning traps, and 30 years of trapping atoms, starting from dipole traps and culminating in 3D optical lattices.

We initialize a single ^{24}Mg ion via trapping and Doppler cooling in a Paul trap, then turn on the optical dipole trap and switch off the Paul trap. The Gaussian trapping beam is focussed down to a waist of 8 μm, has a power of up to 200 mW and is detuned by $7000{\cdot}\Gamma$ from the $S_{1/2} \leftrightarrow P_{3/2}$ transition. The time dependence of the optical trapping probability is investigated and the ions survival detected via resonance fluorescence in the reactivated Paul trap. With experimentally measured lifetimes of single ions of more than 3 ms, the lifetime is mainly limited by recoil heating of the dipole trap. Heating due to the transfer from Paul to optical trap turns out to be on the order of 1 mK at most.

In the future, heating processes could be reduced by using different laser systems with higher power and larger detuning. Furthermore, the lifetime could be extended by cooling the ion in the dipole trap. Doppler cooling, however, seems to be ineffective in the presence of strong Stark shifts. Possible cooling schemes might include alternating trapping and Doppler cooling cycles or sympathetic cooling in a cloud of atoms. Starting with ground-state cooled ions or directly photo-ionizing trapped atoms might reduce cooling requirements.

We argue that, with state-of-the-art (laser) technology, it should be possible to extend optical ion trapping to optical lattices, providing a scalable basis for quantum simulations. In contrast to atomic systems, these would offer long range interactions and individual addressability. Furthermore, trapping ions and atoms in the same optical trap, a potentially intriguing interplay between neutral and charged particles could be explored in quantum simulations and ultra-cold chemistry experiments. In the latter, in particular, the minimal collision energy would not be limited by micromotion-induced heating.

[1] Ch. Schneider, M. Enderlein, T. Huber and T. Schätz, “Optical Trapping of an Ion”, arXiv:1001.2953v1 [quant-ph]

DROM-spectroscopy in pure paraffin wall-coated cell

E. Breschi[1], N. Castagna[2], G. Mileti[1] A. Weis[2], H. G. Robinson[3], S. Knappe[3]

[1]*Time and Frequency Laboratory, University of Neuchâtel, Neuchâtel, Switzerland*
[2]*Physics Department, University of Fribourg, Switzerland*
[3]*Time and Frequency Division, NIST Boulder, U.S.*

Today the study of anti spin-relaxation coating materials (introduced in cell spectroscopy in 1950s[1]) is of a new interest in view of the miniaturization of quantum devices. Even though the most efficient coatings (the paraffins) are not compatible with micro-fabrication processes, the study of atoms colliding with this coating can help identify new coating materials[2].

In this communication we report on our study of the Zeeman relaxation rate dependence on the length of the paraffin molecules. Paraffin is the common name for alkalane hydrocarbons whose length (n) is characterized by the group $CH_3{-}(CH_2)_{(n-2)}{-}CH_3$. The paraffin typically used in cell spectroscopy is a mixture having $20 \leq n \leq 40$. Our study is based on the use of spherical ^{87}Rb-cells (16 mm radius) coated with pure paraffins with $n = 20, 24, 40$, and 60. The spectroscopy method used for our study is the Double-Resonance Orientation Magnetometer (DROM) or M_x-technique[3]. The atoms are irradiated by a DFB laser whose frequency is stabilized to the hyperfine transition $F_g = 1 \rightarrow F_e = 2$ of the ^{87}Rb D1-line using a separated un-coated cell. The atoms are placed in a static magnetic field at $45°$ with respect to the laser propagation vector and a rf magnetic field probes the resonance causing variations of the vapor transmission. For each n-value a set of DROM signals has been recorded by varying the optical power in the range $(1, ..., 10)$ μW. In order to isolate the effect due to the wall-collisions from the set of measurements we extrapolate the values of the population and coherence relaxation rates i.e., $(\Gamma_{01}/2\pi)$ and $(\Gamma_{02}/2\pi)$, respectively, to zero optical intensity. We observed that $(\Gamma_{01}/2\pi)$ and $(\Gamma_{02}/2\pi)$ increase linearly (at different rates) with the length n. The results can be explained by accounting for the strength of the physical binding between paraffin molecules in the coating layer. The interaction between two paraffin molecules is a dipole-dipole interaction whose strength depends on n and on the molecule geometry. On the other hand the binding energy determines the potential attracting the alkalis to the coating surfaces[4] in which the relaxation mainly occurs. Further analyses are in progress in order to characterize more in detail the observed results.

In LTF this activity has been supported by the SNF (subsidy n. 200020-118062) and by the Association Suisse pour la Recherche Horlogère (ASRH). E. Breschi wants to thank the Commission Egalité (University of Neuchâtel) for the assignment of the Subvention Egalité which allows her to participate at this conference.

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[4]J. Vanier and C. Audoin, The quantum physics of atomic frequency standard, Adam-Higler (1986)

High Power Narrow Linewidth Fiber Amplifiers for Atomic Physics

Jianwu Ding[1], Bryce Samson[1], Chiachi Wang[1], Kanishka Tankala[1], Jesse Andregg[2], Adrian Carter[1],

[1]*Nufern, 7 Airport Park Road, East Granby, CT 06026, USA*
[2]*Evans and Sutherland, 770 Komas Drive, Salt Lake City, UT 84108, USA*

Here we present an overview of the recent progress in narrow linewidth high power fiber amplifiers. As one of the enabling technologies for atomic physics, the ultra-narrow linewidth (sub 5kHz) fiber amplifiers with up to 100W output power at 1μm and 1.5μm, and up to 600W in the 2μm wavelength regime have recently been developed. By selectively tuning across the inherently broad spectral linewidths of Yb, Er and Tm emissions and coupled with recent advances in highly efficient CW nonlinear wavelength conversion, a broad range of narrow linewidth laser sources (from deep UV through IR and indeed up to 2400nm) can now be generated with these high power narrow linewidth fiber amplifiers.

- The main limitation on the achievable output power with Gaussian or Gaussian-like spatial beam quality comes from Stimulated Brillouin Scattering (SBS). With the implementation of the improved fiber designs and various SBS-mitigation techniques, the SBS limit has been greatly increased in recent years. [1] [2]
- Up to 20W of narrow linewidth ($<$ 5kHz) with a single spatial mode output has been demonstrated at 1064nm in a compact OEM package. By employing a large-mode-area (LMA) fiber, up to 100W has also been demonstrated with a close to single mode spatial beam profile. In addition, multiple 40W single frequency amplifiers (SFA) have been deployed around the world for atomic applications.
- Similarly, 10W compact OEM amplifier modules featuring a single spatial mode beam profile and operating at 1550nm have been made available, and up to 100W using LMA fiber with a 25μm core diameter and supporting a Gaussian-like spatial beam profile.
- Because the SBS gain is inversely proportional to the square of the laser wavelength [2], the SBS threshold for 2μm light is significantly higher than that in the 1μm regime (for fibers with the same mode field diameter (MFD)). Furthermore, the MFD at 2μm is also larger than that at 1μm for fibers with the same core diameter and numerical aperture. Consequently, amplified output of up to 600W has been demonstrated at 2040nm and was indeed limited only by the available pump power.

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Precision frequency measurement of $2^2S_{1/2} \rightarrow 3^2S_{1/2}$ transition of atomic lithium

Hshan-Chen Chen[2], Yu-Hung Lien[1], Jim-Zen Chen[1], Jyun-Yu Tian[2], Kuan-Ju Lo[1], Jow-Tsong Shy[1,2], Yi-Wei Liu[1]

[1]*Department of Physics, National Tsing Hua University, Taiwan, R.O.C.*
[2]*Institute of Photonics Technologies, National Tsing Hua University, Taiwan, R.O.C.*

We report the absolute frequency measurement of $2^2S_{1/2} \rightarrow 3^2S_{1/2}$ transition of atomic lithium using the Doppler-free two-photon spectroscopy and the accuracy is better than 100 kHz (9.8x10^{-11}). As the simplest three-electron atomic system and lightest alkali atom, lithium receives extensive studies especially the high precision calculation in recent years. Meanwhile, the discovery of exotic halo nuclear structure in lithium isotopes also offers a new opportunity to study nuclear force. Recent calculations of 2S-2P and 2S-3S transition energies and the mass-dependent isotope shifts reported a relative accuracy of better than 1×10^{-7} and 5×10^{-6}, respectively. In the meantime, the progress in experimental of recent work mostly follows the low-lying states with interest. A series of experiments in GSI[1,2] , and TRIUMF-ISAC[3], gave the new values of isotope shifts in 2S-3S transitions of Li with precision better than 10 kHz and determined the nuclear radii of the different isotopes via the two-photon laser spectroscopy. Among these studies, the high precision spectroscopy always serves as a prominent tool.

Our experiment is achieved by the Doppler-free two-photon spectroscopy. A 735 nm Ti:Sapphire laser, which is pumped by a diode-pumped 532 nm solid state laser (Coherent, Verdi V-10), is used as the exciting laser. The 1 W laser outputs is amplitude-modulated by an optical chopper at 690 Hz and excites a weakly collimated atomic lithium beam and the two-photon transition is monitored by the cascading 2P-2S fluorescence observed by PMT. The signal-to-noise (SNR) ratio of the strongest line ^{7}Li (F=2-2) is approximately 150. The laser frequency is scanned by offset-locking to a GPS-based optical frequency comb (Repetition Rate $\approx$ 1 GHz) with the accuracy of 1×10^{-12}. The laser frequency is determined by a wavemeter with 1 GHz resolution and the optical frequency comb. The AC stark shift and the isotope shift were also being investigated. We fit the observed spectrum with a Voigt function and determine the line center. Our results show good agreements with previous experiments[4].

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Nonlinear spectroscopy of Tl $6P_{1/2}$-$7S_{1/2}$ transition

T.L. Chen[1], I. Fan[1], Y.W. Liu[2]

[1]*Dept. of Phys., Nat. Tsing Hua Univ., Hsinchu 30013, Taiwan*
[2]*Electronic address: ywliu@phys.nthu.edu.tw*

Thallium (Tl), with its three valence electrons, is the second simplest atom (after Cs) for which the parity non-conservation (PNC) has been observed experimentally.[1] A many-body perturbation theory combined with the configuration interaction has been developed to calculate the PNC effect in Tl.[2] To examine the accuracy of this theoretical approach, various physical quantities, such as hyperfine splittings and transition energies should be calculated and compared to experiments. In this work, we carried out the preliminary fluorescence spectroscopy measurement for the $6P_{1/2}$-$7S_{1/2}$ transitions of Tl. Our technique is comprised of two counter propagating 377 nm laser beams (frequency doubled from a 755 nm source) “perpendicularly” intersecting with the Doppler reduced (via two concentric slits) Tl atomic beam. The frequency scanning of the laser source results in a Lamb dip like feature on the spectra that can be used to locate the resonance position precisely (See Fig. 1). Comparing with a single pass fluorescence spectrum, it is found that this dip feature originates from the superposition of the two passing beams plus the saturation effects. The superposition contribution can be demonstrated by the control of the dip symmetry via the reflecting beam’s angle, similar to what’s done previously.[3] The saturation effect, on the other hand, is a typical phenomenon when the excitation intensity is well above the absorption limit of the atoms.[4] Any non-orthogonality between the atom beam and the laser beams is sufficient to produce this alignment-independent dip loaction. We fit all of our double pass spectra by summing two Voigt functions minus a Doppler free (Lorentzian) peak. As the next step, we plan to combine this Lamb dip like feature with a femtosecond frequency comb to allow ultra precise determinations of the absolute frequencies of Tl $6P_{1/2}$-$7S_{1/2}$ transition.

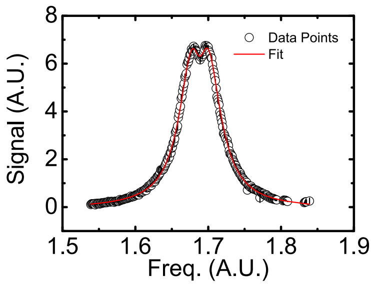

Figure 1: *One of the typical hyperfine transitions of Tl $6P_{1/2}$-$7S_{1/2}$ showing the Lamb dip like feature.*

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[2]M.G. Kozlov and S.G. Porsev, Phys. Rev. A 64, 052107 (2001).
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[4]W. Demtroder, Laser Spectroscopy, Springer-Verlag, Berlin, 1981.

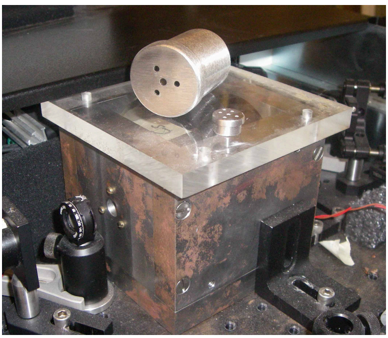
Towards a chip-scale laser lock for space-borne applications

C. Lee[1], G. Iwata[1], E. Corsini[1], J.M. Higbie[2], M.P. Ledbetter[1], S. Knappe[3], J. Kitching[3], D. Budker[1,4]

[1]*Department of Physics, University of California, Berkeley, CA 94720-7300*
[2]*Department of Physics, Bucknell University, Lewisburg, PA 17837*
[3]*Time and Frequency Division, NIST, Boulder, CO 80305*
[4]*Nuclear Science Div., Lawrence Berkeley National Laboratory, Berkeley CA 94720*

Progress in microelectromechanical fabrication has led to the realization of chip scaled alkali vapor cells and corresponding miniature and chip-scaled atomic magnetometer and atomic clocks[1], compatible with fieldable and space-borne applications.

We report on the realization of two miniature laser locking devices based on the dichroic Atomic Vapor Laser Lock (DAVLL) design of Ref.[2]. One is a stand-alone device with a small alkali vapor pyrex cell, the other smaller device has a chip-scaled alkali vapor cell and an internal resistive heater. Both constructions have a layer of mu-metal shielding to reduce the magnet external magnetic field to a few mG. Both designs are based on linear Faraday rotation and dichroism, and use differential polarization-detection for common-mode noise rejection. The use of Doppler-broadened profiles allows the laser to be locked at any point within the absorption line (up to 1 GHz span) and stabilizes the laser optical frequency to within ~1 MHz. The DAVLL of Ref.[2] as well as the two miniature devices are shown in Fig. 1. Both designs, in principle, can also be used in Doppler-free configuration[3]. The chip-scaled atomic vapor device is well suited for compact earth-field magnetometers and space-borne applications.



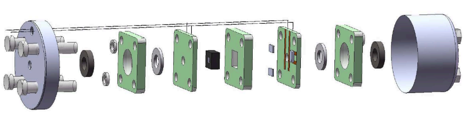


Figure 1: *Left: The larger/older construction[2] (bottom) is shown for size comparison. The top two cylinders are the miniature DAVLLs described above; the rightmost one is the chip-scaled device (≈ 1/2in × 1/2in.) which is also shown on the Right in assembly mode*

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Sponsors: ONR, NURI, ARPA, NIST, U.S. Dept. of Energy.

A multi-functional platform to investigate nonlinear effects in vapor cells with application to magnetometry and clocks

E. Corsini[1], T. Karaulanov[1], D. Budker[1,2],
[1] *Department of Physics, University of California, Berkeley, CA 94720-7300*
[2] *Nuclear Science Div., Lawrence Berkeley National Laboratory, Berkeley CA 94720*

We report on the construction and on the results using a multi-functional platform (Fig. 1) with the ability to quickly switch between alkali elements, hyperfine lines, and pump and probe beam configurations. The platform includes dual distributed feedback (DFB) lasers (Cesium-D2 and Rubidium-D1), beam combining, separate pump and probe beams, dual orthogonal, amplitude modulated pump beams, dual dichroic atomic vapor laser locks (DAVLL)[1], and dual balanced polarimeters to allow for dual alkali species vapor cells. The laser lock-point can also be tuned to the maximum of a given atomic clock resonance and/or to maximize a hyperfine ground state Zeeman coherence using feedback loops. The feedback involving the Zeeman coherence directly modulates the pump beam in a self oscillating loop as described in Ref.[2]. The multi-functionality purpose allows one to perform well characterized measurements needed as input for quantitative modeling. Results will be presented at the conference.

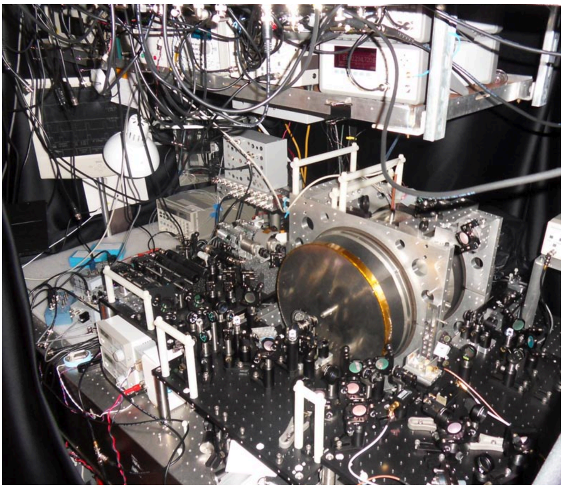

Figure 1: *The apparatus is shown with a four-layer mu-metal shield and four optical platforms supporting all necessary optical elements.*

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Sponsors: ONR, MURI, U.S. Dept. of Energy (LBNL Nuc. Sc. Div. Contr. DE-AC03-76SF00098).

Cavity-Enhanced Direct Frequency Comb Velocity Modulation Spectroscopy

K.C. Cossel, L.C. Sinclair, W.A. Ames, J. Ye, E.A. Cornell

JILA, National Institute of Standards and Technology and University of Colorado
Department of Physics, University of Colorado, Boulder, Colorado

Precision spectroscopy of molecular ions is important for a wide range of applications in both physics and chemistry. For example, electron spin resonance spectroscopy of HfF^+ and ThF^+ will help search for the electron electric dipole moment (eEDM) due to the large electric field enhancement present in these molecules and the long coherence times provided by trapped ions[1]. Additionally, accurate, high-resolution spectra of ions such as H_3^+ and CH_5^+ provide rigorous tests and challenges for ab initio quantum computations[2,3]. Furthermore, the identification of molecular ions in the interstellar medium and accurate measurements of ion-neutral reaction rates are both critical to the understanding of chemistry in interstellar clouds[4]. We have developed a novel technique for broad bandwidth and high resolution survey spectroscopy of molecular ions. Velocity modulation spectroscopy (VMS) in an AC discharge[5] is a well established method of producing ions in relatively high abundance and providing discrimination between ions and neutral absorptions. A new VMS setup using counterpropagating beams in a ring cavity and coherent optical subtraction of the beams at the cavity transmission increases the sensitivity and neutral signal rejection of standard VMS systems. We then combine this approach with cavity-enhanced direct frequency comb spectroscopy[6] to provide a broad and simultaneous spectral bandwidth while maintaining high absolute accuracy and ion sensitivity. This is accomplished using a 3 GHz Ti:Sapphire frequency comb and a two-dimensional imaging system with a VIPA etalon and cross-dispersing grating capable of resolving single comb modes. Detection is accomplished using a 2D lock-in camera, which performs lock-in detection on every pixel synchronized to the AC discharge frequency. This system provides high resolution spectra (better than 30 MHz) across almost 4 THz in a single scan. We will present characterization of the system performance using the (4, 2) band of the $A^2\Pi \rightarrow X^2\Sigma^+$ transition in N_2^+, demonstrating absorption sensitivities of $1\text{x}10^{-5}$ cm^{-1} over 4 THz in under an hour. In addition, we will also present progress towards characterization of the previously unobserved $^3\Delta_1$ level in HfF^+ and its couplings to excited electronic levels, which is important for the JILA eEDM experiment.

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Periodically locked continuous-wave cavity ringdown spectroscopy

Dipankar Das

University of Otago, Dunedin, New Zealand

We demonstrate a simple periodically locked cw cavity ringdown spectroscopy (CRDS) technique that enables a very large number of ringdown events to be rapidly acquired. This is an alternative method for repetitive cavity-locked cw CRDS scheme of Bucher[1] *et al*. and Fox[2]. In our method an external cavity diode laser (ECDL) is locked to a high-finesse cavity by PDH method and ringdown is obtained by periodically switching the light entering the cavity with an AOM. After each ringdown, the light to the cavity is switched back on and cavity lock is rapidly reacquired. This has the advantages of the scheme by Fox[1] *et al* but eliminates the possibility of exciting the higher-order transverse mode of the cavity and producing feedback to the ECDL. In addition, there is no need to switch off the frequency sidebands used for cavity locking and no possibility of residual transmission through the cavity. In the experiment as many as 20,000 ringdown events per second are obtained. Limited by our relatively modest digitization rate, we obtained a minimum detectable absorption loss of 2.83×10^{-9} cm^{-1}. The experimental set up is shown in the Fig.1a and absorption profile of oxygen a$^1\Delta_g \leftarrow$X $^3\Sigma_g^-$ transition at 7882.39 cm^{-1} (1270 nm) is shown in Fig.1b to demonstrate the method.

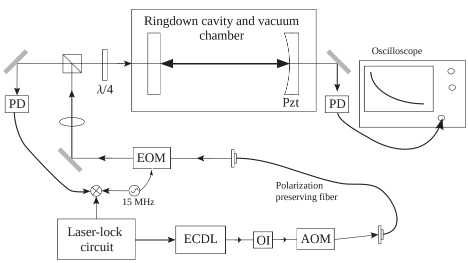

Fig 1a

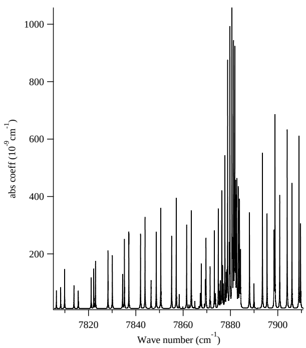

Fig 1b

Figure 1: *(a) Experimental set up for periodically locked CRDS. ECDL - external cavity diode laser, OI - optical isolator, AOM - Acousto-optic modulator, EOM - electr-optic modulator, PD-Photodiode. (b) Oxygen absorption profile at 7882.39 cm^{-1} (1270 nm).*

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Collisions between cold metastable neon atoms in the presence of a resonant light field

R.D. Glover, D.E. Laban, R.T. Sang

Centre for Quantum Dynamics, Griffith University, Brisbane, QLD, Australia

The focus of a number of experiments in recent years is the modification of collision dynamics between extremely cold atoms when under the influence of a near-resonant light field. The interaction potential can be significantly altered and it is even possible to produce purely long-range molecules when two colliding atoms absorb a photon in a process known as photoassociation [1] [2]. Collisions involving metastable noble gas species are unique due to the high probability of Penning and associative ionisation and the lifetime of a molecule formed via photoassociation is expected to be short when compared to a vibrational period [3]. In spite of these difficulties, photoassociation has been demonstrated using metastable He [3] [4]. However, for the other metastable noble gases, molecular formation is yet to be observed. Katori and Shimizu (1994) and Walhout *et al.* (1995) have reported on the use of an auxiliary laser to control ionisation rates in metastable Kr gas and metastable Xe gas, respectively [5] [6].
We report on progress towards photoassociation of cold ($\sim$1 mK) metastable Ne ($^3P_2$) gas in a magneto-optical trap (MOT). Modification of the ionising collision rate is demonstrated when a laser tuned close to the $^3P_2$ to $^3D_3$ cooling transition is used to facilitate interactions between a pairs of trapped metastables.

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Hyperfine structure of low-lying states of ^{14,15}N

T. Carette[1], M. Nemouchi[2], P. Jönsson[3], M.R. Godefroid[1]

[1]*Université Libre de Bruxelles, Brussels, Belgium*
[2]*Laboratoire d'Électronique Quantique, USTHB, El-Alia, Algiers, Algeria*
[3]*Center for Technology Studies, Malmö University, Malmö, Sweden*

Determination of hyperfine structure constants has various astronomical interests. For ground and metastable states, hyperfine structures can often be determined with good accuracy, providing precious guidelines for ab initio calculations. For excited states that are available only through sub-doppler methods in the optical region the experimental values are less reliable, and theoretical evaluations can bring useful information. In 1943, Holmes[1] measured a surprisingly large variation of the specific mass isotope shifts from one multiplet component to another in some transitions between the configurations $2p^2 3s \rightarrow 2p^2 3p$ of ^{14,15}N. Although this observation was confirmed by sub-doppler spectroscopy experiments[2,3], Jennerich et al.[3] pointed out that the experimental isotope shift values are critically dependent of the interpretation of the hyperfine structures of the ^{14}N and ^{15}N spectra. In the conclusions of their work, they appealed for further theoretical investigation to confirm observations.

Hyperfine structure parameters were calculated recently by Jönsson et al.[4] for the $2p^2(^3P)3s\ ^4P_J$, $2p^2(^3P)3p\ ^4P^o_J$ and $2p^2(^3P)3p\ ^4D^o_J$ levels, using the ab initio multiconfiguration Hartree-Fock method (MCHF). The resulting theoretical hyperfine coupling constants are in complete disagreement with the experimental values of Jennerich et al.[3] deduced from the analysis of the near-infrared Doppler-free saturated absorption spectra. We propose a new interpretation of the recorded weak spectral lines. If the latter are reinterpreted as crossovers signals, a new set of experimental hyperfine constants is deduced, in very good agreement with the ab initio predictions. The ambiguity in the assignation of the recorded spectra is due to strong line shape perturbation. The present analysis washes out the J-dependency of specific mass shift (SMS) found for $3p\ ^4P^o$ and $3p\ ^4D^o$ multiplets. On the contrary, a somewhat large SMS J-dependency is deduced for the even parity $3s\ ^4P$ multiplet. This effect is enhanced by the strong non-relativistic mixing with the $1s^2 2s 2p^4\ ^4P$ term, which depends strongly of the total atomic electronic momentum J once relativistic corrections are added.

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Enhanced laboratory sensitivity to variation of the fine-structure constant using highly-charged ions

J.C. Berengut, V.A. Dzuba, V.V. Flambaum

School of Physics, University of New South Wales, Sydney, NSW 2052, Australia

The sensitivity of atomic transitions to the fine-structure constant, α, is well known to increase with the atomic number as Z^2. However the relativistic corrections also rapidly increase with the effective charge Z_{eff} which an external electron "sees". These corrections are proportional to Z_{eff}^2. In the simple case of one electron above closed shells, $Z_{\text{eff}} \approx Z_i + 1$ where Z_i is the ion charge. Therefore, highly charged ions are expected to have larger relativistic corrections, and hence a stronger sensitivity to possible variation of α.

Unfortunately the interval between energy levels also increases as Z_{eff}^2, which can take the transition frequency outside the range of lasers. However, in some cases the Coulomb degeneracy and configuration crossing phenomena can help. For example, in a neutral atom an electron energy level with larger orbital angular momentum is significantly higher than a level with lower orbital angular momentum but with the same principal quantum number. On the other hand in the limit of hydrogen-like orbitals, the energy is dominated by the principal quantum number and is nearly independent of orbital angular momentum. Therefore, as one increases the ion charge there exists a "crossing point" where the orbital energies are close. Such an ion may have transitions within the range of lasers but with very high sensitivity to α-variation.

Using recent improvements in laboratory trapping and cooling of multiply-charged ions, this idea may be realised as the most precise experimental probe of α-variation to date.

Interpreting laboratory and observational limits on variation of fundamental constants in terms of possible spatial variation

J.C. Berengut, V.V. Flambaum

School of Physics, University of New South Wales, Sydney, NSW 2052, Australia

We discuss how different existing studies of variation of fundamental constants can be reinterpreted in terms of spatial variation. For example, Earth-based atomic clock limits on variation of α can be combined with astrophysical measurements to provide limits on spatial variation of α. Additional limits on α (and other fundamental constants) can be obtained from the Oklo natural nuclear reactor.

In addition, we propose a method to test whether spatial variation of fundamental constants existed during the epoch of big bang nucleosynthesis. Using existing measurements of primordial deuterium abundance we find very weak hints that such a signature might exist, but the paucity of measurements precludes any firm conclusion. In addition we examine existing quasar absorption spectra data on variation of the electron-to-proton mass ratio μ and $x = \alpha^2 \mu g_p$ (where g_p is the proton g-factor) for evidence of spatial variation.

A New Limit on CPT and Lorentz Violation Using a Rotating K-^{3}He Co-magnetometer

J.M. Brown, S.J. Smullin, T.W. Kornack M.V. Romalis

Princeton University, Princeton, New Jersey 08544, USA

A K-^{3}He co-magnetometer contains overlapping, coupled spin ensembles of high density polarized K vapor and ^{3}He nuclei that cancel external magnetic fields by a factor of $10^3 - 10^4$, but remain sensitive to anomalous electron and neutron spin couplings. Our 2.5 cm spherical vapor cell contains 6×10^{13}/cm^3 K and 2.5×10^{20}/cm^3 ^{3}He. The cell resides inside a compact 3-layer μ-metal and inner ferrite magnetic shield to further reduce magnetic interactions by a factor of 10^8. The co-magnetometer, including lasers and vibration isolation platform, are operated in a 1 Torr vacuum to achieve an equivalent magnetic sensitivity of 2 fT/$\sqrt{\text{Hz}}$ at 0.02 Hz. We mount the vacuum bell jar and control electronics on a rotating platform allowing 180° reversals of the apparatus every 22 seconds. Since the co-magnetometer is also a sensitive gyroscope, reorientation of the apparatus with respect to Earth's rotation axis provides a significant contribution to our signal of approximately 277 fT. We collect data in the North-South and East-West orientations, corresponding to the maximum and zero of the gyroscope signal (see Fig. 1). Data taken along these two orthogonal directions are sensitive to different systematic effects. A sidereal, out-of-phase modulation in the two signals would provide evidence for a CPT or Lorentz Violating field. We have automated the experiment to run 24 hours a day and have achieved uninterrupted operation over several weeks.

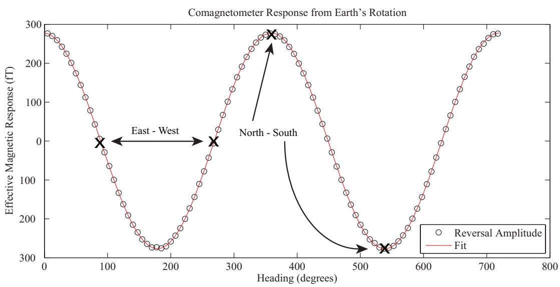

Figure 1: *Gyroscope response from reorientation of the apparatus with respect to Earth's rotation axis.*

After 140 days of integration spread over 9 months, we have achieved an effective sensitivity of 0.023 fT to the proposed CPT and Lorentz violating field. The co-magnetometer is sensitive to the difference in electron and nuclear spin couplings. Using the current limit for anomalous spin coupling to the electron[1], we constrain the anomalous spin coupling to the neutron, $|b^n_\perp|$, to less than 4.2×10^{-33} GeV. This represents the tightest bound of Lorentz Violation coupling to fermions.

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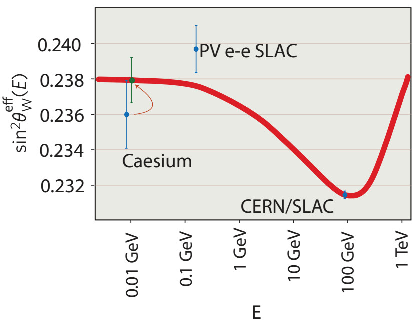
Improved test of the standard model of elementary particles with atomic parity violation

S.G. Porsev, Kyle Beloy, Andrei Derevianko

Department of Physics, University of Nevada, Reno, NV 89557, USA

In physics, the vacuum is never still. Each particle carries a cloud of continuously sprouting virtual particle-antiparticle pairs. The strength of the mutual interaction between two particles becomes dependent on their relative collision energy: at higher energies, the collision partners tend to penetrate deeper inside the shielding clouds. For electroweak interactions, the Standard Model (SM) of elementary particles yields an answer for such an energy-dependence (or "running"). Collider experiments provide reference points at high energies. Here we improve the accuracy of probing the least-energetic electroweak interaction. We extract the strength of the parity-violating interaction of atomic electrons with quarks of the caesium nucleus by combining measurements with our calculations. Our analysis is the most accurate to-date test of the low-energy electroweak sector of the SM. For low energies, where the shielding clouds are penetrated the least, previous analyses were consistent with no running. Our precision result confirms the fundamental running. Together with the results of high-energy collider experiments, we demonstrate the validity of the predicted running of the electroweak force over an energy range spanning four orders of magnitude (from ~ 10 MeV to ~ 100 GeV).

Additionally our work places new limits on the masses of extra Z bosons (Z'). Our raised bound on the Z' masses carves out a lower-energy part of the discovery reach of the Large Hadron Collider. At the same time, a major goal of the LHC is to find evidence for supersymmetry (SUSY), one of the basic, yet experimentally unproven, concepts of particle physics. Our result is consistent with the R-parity conserving SUSY with relatively light (sub-TeV) superpartners. This raises additional hopes of discovering SUSY at the LHC.



Details may be found in the paper: S. G. Porsev, K. Beloy and A. Derevianko, Phys. Rev. Lett. 102, 181601 (2009)

Atomic Ionization by keV-scale Pseudoscalar Dark Matter Particles

V.A. Dzuba[1], V.V. Flambaum[1], M. Pospelov[2,3]

[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*
[2]*Department of Physics and Astronomy, University of Victoria, Victoria, British Colombia, V8P IAI, Canada*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2J 2W9, Canada*

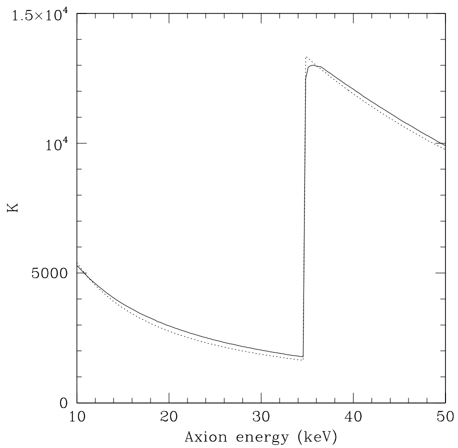
Using the relativistic Hartree-Fock approximation, we calculate the rates of atomic ionization by absorption of pseudoscalar particles (called axions for short, although they differ from QCD axions by their mass) in the mass range from 10 to $\sim$ 50 keV. We present numerical results for atoms relevant for the direct dark matter searches (*e.g.* Ar, Ge, I and Xe), as well as the analytical formula which fits numerical calculations with few per cent accuracy and may be used for multi-electron atoms, molecules and condensed matter systems.

The results for ionization cross-section are presented in a form

$$\sigma_a(\epsilon_a) = \left(\frac{\epsilon_0}{f_a}\right)^2 \frac{c}{v} K(\epsilon_a) a_0^2,$$

where ϵ_a is the energy of a dark matter particle, ϵ_0 is an energy scale, c is speed of light, v is the particle velocity in the laboratory frame, $a_0 = 0.52918 \times 10^{-8}$ cm is Borh radius, and $K(\epsilon_a)$ is dimensionless function of the energy which is found from the calculations.

Fig. 1 shows as an example the $K(\epsilon_a)$ function for Xe atom. Solid line represents the results of the Hartree-Fock calculations, dotted line - the result of analytical fitting of the calculations. The fitting is done for $18 < Z < 60$ and for dark matter particle energies from 10 to 50 keV.



Trapping of Yb ions in a wide optical access trap: Towards optimum free-space photon-atom coupling

R. Maiwald[1,2], A. Golla[1,2], S. Heugel[1,2], A.S. Villar[2], V. Elman[2], B. Chalopin[2], M. Sondermann[1,2], G. Leuchs[1,2]

[1]*Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Erlangen, Germany*
[2]*Max Planck Institute for the Science of Light, Erlangen, Germany*

In the last decades a wide range of possibilities has been developed to study the interaction of light and matter on the single quantum level. In our particular experiment we aim at efficient coupling of single photons and single ions without the need for a cavity. Taken to the extreme, such a setup would enable perfect absorption of a single photon by a single atom. To this purpose, the overlap between the incident light wave and the radiation pattern of the corresponding atomic transition should be reasonably close to unity. In particular, the accessible solid angle has to be maximized. Using a deep parabolic mirror one can focus down light to a single ion from nearly the full solid angle[1]. There exist different possibilities for trapping in a paraboloid while maintaining high optical accessibility. We present simulations for three selected Paul trap geometries: A segmented parabolic mirror itself forms the trap electrodes maximizing optical access (Fig. 1a). Another possibility is to combine a two needles trap (cf. Deslauriers *et al.*[2]) with a parabolic mirror (Fig. 1b). The two needles trap can be reduced to a trap with single needle structure (Fig. 1c). A so called stylus trap with geometrical optical access of 96% has been developed and tested with $^{24}Mg^+$ ions[3] and $^{174}Yb^+$ ions. Currently we are setting up an experiment to combine a stylus trap with a parabolic mirror made of aluminium. We present the characterization of the stylus trap with $^{174}Yb^+$ ions and give a detailed overview of the current experimental status concerning the combination of trap and parabolic mirror.

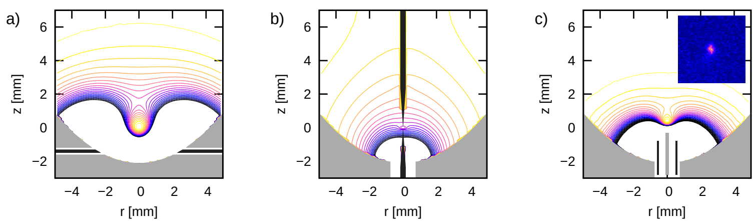


Figure 1: *Simulations of pseudo-potentials of **a)** segmented parabolic mirror trap **b)** two needles trap **c)** stylus trap, the inset shows the fluorescence of a single Yb^+ ion in a stylus trap with the paraboloid replaced by a planar electrode. (DC electrodes: light gray, RF electrodes: dark gray)*

[1]M. Sondermann *et al.*, Applied Physics B, **89** (4), 489-492 (2007)
[2]L. Deslauriers *et al.*, Phys. Rev. Lett. **97**, 103007 (2006)
[3]R. Maiwald *et al.*, Nature Physics **5**, 551-554 (2009)

A micro-fabricated surface electrode ion trap with integrated optical resonator

P.F. Herskind, M. Shi, S.X. Wang, T.H. Kim, Y. Ge, W. Chen, V. Vuletic, I.L. Chuang

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

We report on an experiment designed to achieve strong coherent coupling between a single ion and the field of an optical resonator, which may be used to achieve faithful transfer of a quantum state between an ion and a photon[1].

In this work, the challenge of combining an optical cavity with an ion trap is approached by integrating the ion trap into the cavity rather than by integrating the cavity into the ion trap, as has been the conventional approach[2]. By taking advantage of the techniques of optical lithography, we have successfully micro-fabricated a linear surface electrode Paul trap on a high-finesse optical mirror. An aperture in the central electrode, above which the ion is trapped, ensures optical access to the mirror and the addition of a second, concave, mirror above the trap allows for the formation of an optical resonator to which the ion can be coupled.

Single to a few ions have been trapped 150 μm above the surface of this trap and held for $\sim$ 1hour, thus demonstrating that the trapping potential is not compromised by the introduction of the mirror, even at such close range.

To support an optical cavity mode with a minimal waist for optimal ion-photon coupling, we have machined concave mirrors with radius of curvature (ROC) of only 50μm-1mm using a CO2 laser[3]. For a single $^{88}Sr^{+}$ ion trapped inside a near-confocal cavity, with a finesse of about 7000 and resonant with the $5\ ^2S_{1/2} \leftrightarrow 5\ ^2P_{3/2}$ transition at 408nm, we expect a cooperativity of about 5 to 10 for ROC=300-500μm of the concave mirror.

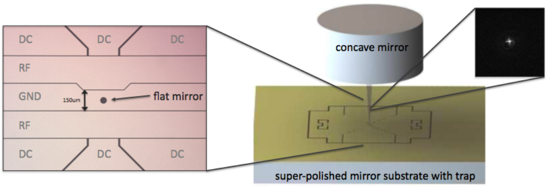


Figure 1: *Schematic of combined trap and optical cavity (not to scale). Insert on left shows microscope image of the trap including the aperture for the mirror. Insert on the right shows image of the first ion trapped 150µm above the plane mirror inside a He-bath cryostat at 5K.*

[1] J. I. Cirac, P. Zoller, H. J. Kimble, H. Mabuchi, Phys. Rev. Lett., 78, 3221, 1997.

[2] M. Keller, B. Lange, K. Hayasaka, W. Lange, H. Walther, Nature, 431, 1075 (2004); P. F. Herskind, A. Dantan, J. P. Marler, M. Albert, M. Drewsen, Nature Phys, 5, 494 (2009); D. R. Leibrandt, J. Labaziewicz, V. Vuletic, I. L. Chuang, Phys. Rev. Lett., 103, 103001 (2009); F. Dubin, C. Russo, H. G. Barros, A. Stute, C. Becher, P. O. Schmidt, R. Blatt, Nature Phys, 6, 350 (2010).

[3] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, J. Reichel, arXiv:1005.0067v1 (2010)

Trapped ytterbium ions for scalable quantum technology

M.D. Hughes, J.J. McLoughlin, A.H. Nizamani, J.D. Siverns, R.C. Sterling,
B. Lekitsch, B. Stein, S. Weidt and W.K. Hensinger

Department of Physics and Astronomy, University of Sussex, Brighton, UK, BN1 9QH

Ion trapping provides a promising tool towards the implementation of quantum information processing, with long coherence times and quantum algorithms being demonstrated. At Sussex, we are concentrating on scaling up ion trap quantum technologies.

By controlling the frequency of the photo-ionisation laser, we achieved isotope selective loading. We demonstrated a simple technique enabling us to measure the resonant $^1S_0 \leftrightarrow {}^1P_1$ transition for several neutral Yb isotopes to $\pm$60MHz absolute accuracy, and isotope shifts to $\pm$30MHz. Our method is also able to determine the mean atomic velocity along the atomic beam and provides appropriate frequency correction factors for realistic ion trap setups that feature non-perpendicular overlap of atomic and photo-ionisation laser.

We have trapped single ytterbium ions in an experimental setup particularly designed for the development of advanced ion trap chips. This setup allows for rapid turn-around time, optical access for all type of ion trap chips and up to 100 electric interconnects. The particular ion trap used features an ion - electrode distance of 310 microns and secular frequencies on the order of 1 MHz and we have observed ion life times in excess of 15 hours. We measured the motional heating rate and obtained a value for the electric field noise of $S_E(1MHz) = (3.6 \pm 1) \times 10^{-11}(V/m)^2Hz^{-1}$ at an ion-electrode distance of 310μm . We have loaded different Yb isotopes and have made more precise atomic transition wavelength measurements accurate to $\pm$120MHz than what had previously been reported.

Sympathetic crystallization of CaH^+ produced by laser-induced chemical reaction

N. Kimura[1], T. Suganuma[1], K. Okada[1], T. Takayanagi[1], M. Wada[2], H. A. Schuessler[3]

[1]*Department of Physics, Sophia University, 7-1 Chiyoda, Tokyo 102-8554, Japan*
[2]*Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Department of Physics, Texas A&M University, College Station, TX 77843, USA*

Sympathetic crystallized molecular ions in ion traps provide the ideal system for precision measurements of molecular vibrational and rotational transitions[1] as well as for studying ultracold molecular ion-polar molecule collisions [2]. Here we investigated sympathetic Coulomb crystallization of CaH^+ ions produced by the laser-induced chemical reaction of $Ca^+(4pP_{1/2})$ + $H_2 \rightarrow$ CaH^+ + H. Since the reaction is endothermic by about 2.3 eV for the ground state Ca^+, the reaction never proceeds without the laser excitations, and thus the cooling lasers (λ = 397 and 866 nm) must be irradiated for the production of CaH^+ ions. Generated CaH^+ ions were confirmed by the observation of secular motion spectra via the Ca^+ fluorescence and the modified fluorescence images of crystallized Ca^+ ions. As shown in Fig1 (a), we successfully observed mixed-species Coulomb crystals of Ca^+ and CaH^+. Due to the existence of the asymmetric direct current voltages by the patch effect by electric charges on the electrodes, the CaH^+ Coulomb crystal was pushed to the upper side of the image. Both of the observed Ca^+ image and the simulated image by the molecular dynamics simulation (Fig.1 (b)) show that the sympathetically cooled CaH^+ ions were also crystallized. From the simulation results, the number of crystallized molecular ions, the secular temperature and the structure was determined [3].

In near future we will apply the crystallized molecular ions to study ultracold molecular ion-polar molecule reactions using a Stark velocity selector.

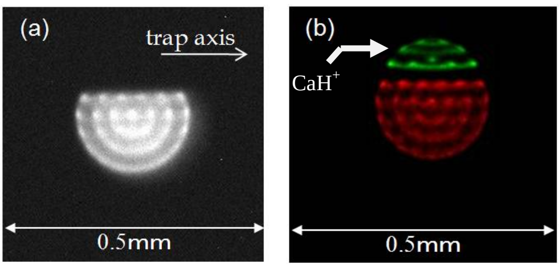


Figure 1: *An observed CCD image (a) and a simulation image (b) of 134* Ca^+ *and 40* CaH^+. *The simulation shows that* CaH^+ *ions are crystallized in the dark region of the upper side of (a).The trapping parameters are* f_{rf} *=5.49 MHz,*V_{ac} *= 171.5 V ,*V_z *= 7.1V.*

[1]M. Kajita *et al.,* J. Phys. B 42, 154022 (2009).
[2]S. Willitisch *et al.,* Phys. Rev. Lett. 100, 043203 (2008).
[3]K. Okada *et al.,* Phys. Rev. A81, 013420 (2010).

State-independent experimental test of quantum contextuality with trapped ions

G. Kirchmair[1,2], F. Zähringer[2], R. Gerritsma[1,2], M. Kleinmann[1], O. Gühne[1,3], A. Cabello[4], A. Blatt[1,2], 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, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria*
[3]*Institut für theoretische Physik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria*
[4]*Departamento de Física Aplicada II, Universidad de Sevilla, E-41012 Sevilla, Spain*

The high control over experimental parameters in ion traps opens up the possibility to do fundamental tests of quantum mechanics. These test are important as it is still debated whether quantum mechanics can be explained with *hidden variable models*. This poster presents the realization of a recent proposal for a state-independent test of quantum contextuality.[1] A part of the poster is dedicated to introducing non-contextual hidden variable models and explaining the proposed measurements. Additionally a gate mechanism that allows for entangling ions without ground state cooling will be explained and experimental results obtained with two ions are presented.[2] The experiment is described in which we apply the gate for a quantum non-demolition measurement of two-ion spin correlations. This technique makes it possible to sequentially measure several compatible observables on a single quantum system and to correlate the measurement results. In this way, we have been able to realize a state-independent test of quantum contextuality. The experimental results[3] demonstrate that the observed correlations cannot be explained by non-contextual hidden variable theories.

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[1]A. Cabello Phys.Rev.Lett. 101, 210401 (2008)
[2]G.Kirchmair, J.Benhelm, F.Zähringer, R.Gerritsma, C.F.Roos, R. Blatt, New. J. Phys. 11, 023002 (2009)
[3]G. Kirchmair, F. Zähringer, R. Gerritsma, M. Kleinmann, O.Gühne, A.Cabello, R.Blatt, C.F.Roos Nature 460, 494 (2009)