A laser-cooled single-atom-on-demand source for Si quantum computing

W. Fairbank, S.A. Lee, W. Czajkowski, J. Kluck

Colorado State University, Fort Collins CO

A promising proposal by B. Kane for a scalable silicon quantum computer requires the placement of ^{31}P atoms 20 nm apart and 10 nm below the surface in pure ^{28}Si to 1 nm precision [1]. This paper presents a scheme for laser cooling and trapping of ^{31}Si atoms in a magneto-optical trap (MOT), detecting by fluorescence when there is only one atom in the trap, resonantly ionizing that one atom near threshold, and softly depositing the single $^{31}Si^+$ ion in Si to nm precision at $\sim$100 eV. A few hours after deposition ^{31}Si beta decays to $^{31}P^+$.

The hyperfine structure and isotope shifts of the 221.7 nm cooling transition for the stable isotopes of Si have been measured with precision for the first time. Sufficient power for the MOT at this wavelength has also been demonstrated. New autoionizing states near threshold have been found and ionization cross sections determined. Progress in laser cooling and laser ablation studies with stable Si atoms will be presented.

This work is supported by the W. M. Keck Foundation.

[1] B. E. Kane, Nature, **393**, 133 (1998).

Simulating ultracold gases using tensor network representations

A.J. Ferris and I.P. McCulloch

The University of Queensland, Brisbane, Queensland, Australia

We investigate and apply a range of novel simulation techniques for simulating entangled quantum systems. In particular, we focus on *tensor network* methods that allow us to calculate both ground state/thermal statistics and dynamics of one-dimensional quantum systems, such as trapped ultracold gases.

Matrix product states (MPS) are an efficient representation for the quantum state of entangled 1D systems, provided that the entanglement in the system is somewhat 'localised'. Traditional MPS techniques rely on a discrete spatial lattice, and standard techniques for discretising continuous models (describing, say, the 1D Bose gas) can be used. On the other hand, Verstraete and Cirac[1] recently outlined a *continuous* MPS representation for describing quantum fields. We describe how this new approach can be implemented accurately and compare its accuracy and efficiency to earlier MPS methods.

In summary, we will outline examples where tensor network representations can be effective in handling thermal, ground state or dynamical problems in 1D ultracold gases. We conclude with prospects for simulating 2D or 3D systems with related methods, and the major challenges yet to be overcome.

[1]F. Verstraete, J. I. Cirac, *Continuous Matrix Product States for Quantum Fields*, Phys. Rev. Lett. 104, 190405 (2010)

High speed multimode atomic memory for a light pulse

T Golubeva[1], Yu. Golubev[1], 0. Mishina[2], J. Laurat[2], A. Bramati[2], E. Giacobino[2]

[1]*V.A. Fock Institute, St. Petersburg State University, 198504 St. Petersburg, Russia*
[2]*Laboratoire Kastler Brossel, UPMC, ENS, CNRS, 4 pl Jussieu, 75005 Paris, France*

We study the coherent storage and retrieval of a very short light pulse in an atomic vapor. We show that, contrary to usual EIT, a very good efficiency can be obtained over a broad signal bandwidth and that the system allows for very good multimode spatial storage.

We consider an ensemble of N three-level atoms in a Λ configuration interacting with two fields, a strong control field and a weak signal field, resonant with the atomic transitions. The signal and the control pulse durations, which are supposed to be equal, are much shorter than the lifetime of the atomic exited state. The control field is a plane wave, while the signal field is spatially multimode field .

We have analytically solved the differential equations describing the evolution in time as well as in 3D space coordinates, which yields a detailed characterization of the memory. For a medium length L and a write pulse duration T_W, we assess the efficiency of the write-in process for each spatial spectral component of the field using the "leakage" i.e. the relative energy $Loss_{\vec{q}}(T_W, L)$ of the signal field that has not been stored and is transmitted through the medium. The dependence of $Loss_{\vec{q}}$ on T_W for different values of L can be calculated very precisely and is shown in Fig. 1. The efficiency increases when the length of the medium is increased. On the other hand, for each length, there is an optimal value of the pulse duration.

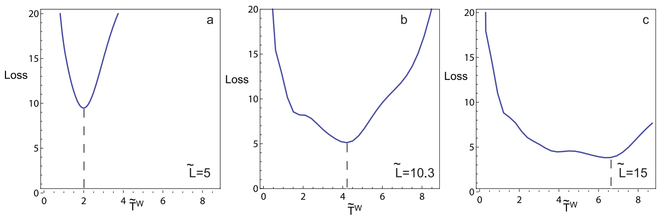


Figure 1: *Transmitted signal field energy (normalized to input field energy) as a function of the normalized pulse duration $\tilde{T}_W = \Omega T_W$, where Ω is the control field Rabi frequency, for three values of the normalized medium length $\tilde{L} = 2g^2 NL/\Omega$, where g is the atom control field coupling coefficient: (a) $\tilde{L} = 5$; (b) $\tilde{L} = 10.3$; (c) $\tilde{L} = 15$.*

The information capacity of the memory scheme is estimated from the number of transverse modes that can be stored in this scheme. In the paraxial approximation, it is equal to $N = S/d^2$, where S is the cell cross section and d is the pixel size, similar to what was predicted for a QND-based quantum volume hologram.

Acknowledgements. The study was supported by the European FET Project HIDEAS (grant No. 221906), by RFBR (No. 08-02-92504, and No. 08-02-00771) and by the Russian-French GDRE "Lasers and Advanced Optical Information Technologies".

Multi-qubit Operations Using Scalable Techniques

D. Hanneke[1], J. P. Home[1], J. D. Jost[1], J. M. Amini[2], R. Bowler[1], T. R. Tan[1], Y. Lin[1], D. Leibfried[1], D. J. Wineland[1]

[1]*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado, USA*
[2]*Georgia Tech Quantum Institute, Atlanta, Georgia, USA*

Quantum information processing (QIP) promises significant gains for some important computational tasks as well as the potential to simulate interesting physical systems. Storing quantum bits (qubits) in the internal states of trapped atomic ions has been a fruitful approach to QIP because of long coherence times and precise interaction with light fields for coherent control and entanglement generation.

Here, we present a complete methods set for scalable ion-trap QIP, including robust qubit storage, single- and two-qubit logic gates, state initialization and readout, and quantum information transport. This combination of techniques enables sustained processing, in which repeated multiple-qubit operations show no loss of performance despite qubit transport over macroscopic distances[1].

We present the first realization of a programmable two-qubit quantum processor[2] and discuss progress towards applying these techniques to three or more qubits.

This work is supported by DARPA, NSA, ONR, IARPA, Sandia, and the NIST Quantum Information Program.

[1]J. P. Home, D. Hanneke, J. D. Jost, J. M. Amini, D. Leibfried, and D. J. Wineland, "Complete methods set for scalable ion trap quantum information processing," Science **325** 1227–1230 (2009)

[2]D. Hanneke, J. P. Home, J. D. Jost, J. M. Amini, D. Leibfried, and D. J. Wineland, "Realization of a programmable two-qubit quantum processor," Nature Phys. **6** 13–16 (2010)

Quantum Information Experiments with Trapped Ions

D. Hayes, W. Campbell, E. Edwards, D. Hucul, K. R. Islam, K. Kim, S. Korenblit, L. Luo, D. Matsukevich, J. Mizrahi, Q. Quraishi, C. Senko, J. Sterk, C. Monroe

JQI, University of Maryland Dept. of Physics, NIST

Much progress has been made toward using trapped ions in quantum information processing tasks [1], yet there continue to be new approaches to the generation of entanglement in trapped ions with an eye toward scaling to much larger systems. I will report on several experiments from the JQI/Maryland ion trap group aimed toward this end. These experiments include the demonstration of an entangling gate between remotely located ions implemented by a joint measurement of their scattered photons [2]. Such a gate might facilitate the scaling requirements in a trapped ion quantum computer and was recently used to carry out a teleportation protocol [3]. This example of entanglement-at-a-distance combined with near-perfect qubit measurements has also allowed the demonstration of a new source of random numbers whose privacy is guaranteed by quantum mechanics [4]. I will also report on progress toward integrating an optical cavity into this system to aide in the collection of the mediating photons, thereby boosting the success rate.

Our group is also developing an apparatus capable of simulating the quantum dynamics of a tunable Ising interaction, generated through spin-dependent dipole forces that modulate the Coulomb interaction [5]. We have recently reported the measured phase diagram of three quantum spins [6] along with a direct measurement of entanglement emerging from a frustrated Hamiltonian [7]. We also show preliminary data on the phase transition from paramagnetism to ferromagnetism in a collection of up to 10 quantum spins, and scaling to larger numbers of spins looks promising.

We also report on our group's recent demonstration of the use of mode-locked laser pulses to carry out single and multi qubit operations [8]. In the regime where many pulses are used, the optical frequency comb concept is used to easily understand how these lasers are used to accomplish tasks that were first developed in the context of cw lasers. In the strong field regime, single qubit operations are carried out on the time scale of 50 picoseconds [9]. Working in this strong pulse regime might allow for the possibility of breaking through the speed limit on traditional entangling gates based on collective motion set by the trapping frequency of ion motion.

This work is supported by the ARO with funds from the DARPA Optical Lattice Emulator (OLE) Program, IARPA under ARO contract, the NSF Physics at the Information Frontier Program, and the NSF Physics Frontier Center at JQI.

---

[1] Wineland/Blatt, Nature (2008)
[2] Maunz, PRL 102, 250502 (2009)
[3] Olmschenk, Science 323, 486 (2009)
[4] Pironio, Nature (2010)
[5] Kim, PRL 103, 120502 (2010)
[6] Edwards ArXiv 1005.4160 (2010)
[7] Kim, Submitted to Nature (2010)
[8] Hayes, PRL 104, 140501 (2010)
[9] Campbell, arXiv:1004.4144 (2010)

Microfabricated asymmetric ion traps for quantum information and simulation

R.C. Sterling[1], P. Srinivasan[2], J.D. Siverns[1], H. Rattanasonti[2], M.D. Hughes[1], M. Kraft[2] and W.K. Hensinger[1]

[1]*Department of Physics and Astronomy, University of Sussex, Brighton, UK, BN1 9QH*
[2]*School of Electronics and Computer Science, University of Southampton, Highfield, Southampton, UK, SO17 1BJ*

Microfabricated ion trap chips are of fundamental importance for the implementation of novel quantum technologies with trapped ions. Using micro-electromechanical (MEMS) fabrication technologies we report design and fabrication of a multi-zone surface-electrode ion trap on a silicon-on-insulator (SOI) wafer in which all dielectrics are optically and electrically shielded. This has been accomplished without the cost of additional complexity of associated with such designs and retains the scalability that makes surface architectures appealing.

We also present a microfabricated two dimensional array of polygon surface electrodes that provide a simple scalable structure in which to create ion lattices. When optimised, are capable of performing quantum simulations. Such an array of ions could provide a fully controllable spin system which would enable the solution of problems currently unattainable by classical computations. By performing boundary element simulations on a variety of different polygon surface geometries. A optimal electrode geometries suitable for microfabircation will be shown that can create a two dimensional ion lattice for use in quantum simulations.

Design of optimum electrode configuration for fast ion separation and the development of junctions within ion trap arrays

A.H. Nizamani, B. Stein, M.D. Hughes and W.K. Hensinger

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

Trapped ions in a rf Paul trap can produce quantum logic gates which are the building blocks of quantum computer. This application can be implemented with a pair of ions and can be extended to a few ions in a single trap. However it is not practical to manipulate many qubits in a single trapping region. Alternative solution demands that qubits can be stored in separate trapping regions memory zones and only be brought together in a single trap processor zones when needed for quantum operations. This scheme can be achieved by using ion traps arrays with the possibility of ion transportation between trapping regions.

To scale to a larger numbers of qubits, segmented electrode structures allow for the creation of multiple trapping zones effectively creating an ion trap array. Such an array, typically implemented as an integrated microchip, allows adiabatic transport of individual ions. The separation of ions within an ion trap array is crucial for most quantum information implementations with trapped ions. We have carried out detailed boundary element simulations in order to obtain optimal electrode configurations in surface ion traps and we will report first results on how such ion trap structures have to be designed for optimal separation to occur.

We also report on our studies for the development of optimal junctions within such ion trap arrays. Potential barriers within the junction region make adiabatic transport of ions through a junction challenging. At the same time, large variations of the ion secular frequency within the ion's shuttling path crossing a junction pose a problem for adiabatic transport. We relate the constraints involved in maintaining high secular frequencies whilst keeping the barrier height small to the low-order multipole expansion of the rf potential to particular junction designs and present results on the design of optimal junctions within surface ion traps.

Single Shot Quantum Gates

S.S. Ivanov[1,2], N.V. Vitanov[2]

[1]*Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria*
[2]*Institut Carnot de Bourgogne, UMR 5209 CNRS, Université de Bourgogne, BP 47870, 21078 Dijon, France*

We propose a new approach for realization of control gates in trapped ions using a series of resonant small area laser pulses. The advantage is that the pulses are of the same type but different phase and address only one ion from the chain. Furthermore, the gate is very insensitive to the applied Rabi frequencies, and consequently a number of experimental obstacles are overcome: lack of calibration, fluctuations of the laser intensity, etc.

Maxwell's demon in the quantum wonderland

S. W. Kim[1,2] T. Sagawa[2] S. De Liberato[2] M. Ueda[2]

[1]*Department of Physics Education, Pusan National University, Busan 609-735, Korea*
[2]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

Maxwell's demon is a hypothetical being of intelligence that was conceived to illuminate possible limitations of the second law of thermodynamics. Leo Szilard made a classical analysis of the Maxwell's demon, considering an idealized heat engine with one molecule gas. The cycle of the the Szilard engine (SZE) consists of three processes: (A) to insert a wall so as to divide a box into two parts, (B) to measure to have information in which side the molecule is, and (C) to attach a weight to the wall and for the molecule in contact with a thermal reservoir of temperature T to push the wall via quasi-static process. As the gas is expanded isothermally, the amount of extracted work is $k_\mathrm{B}T\ln 2$, where k_B is a Boltzmann constant. An immediate question here might be if this violates the second law of thermodynamics. The reason is that during the isothermal expansion the entropy ($k_\mathrm{B}\ln 2$) as well as heat ($k_\mathrm{B}T\ln 2$) enters the engine, but this entropy is not returned back to the environment during the whole cycle. Now it is commonly accepted that the measurement process including erasure or reset of memory requires the minimum cost of energy associated with the entropy decrease of the engine, at least by $k_\mathrm{B}\ln 2$, which saves the second law.

Although SZE is a quantum-mechanical object, namely an engine with a single molecule, only the classical thermodynamic behavior with the emphasis on the information entropy has been considered so far. Here, we present the first complete quantum analysis of the SZE, and report two important findings. First, we derive an analytic expression of the quantum mechanical work performed by a quantum SZE containing arbitrary number of molecules, which reads

$$W_\mathrm{tot} = -k_\mathrm{B}T\sum_{m=0}^{N} f_m \ln\left(\frac{f_m}{f_m^*}\right), \tag{1}$$

where the definition and the physical meaning of f_m and f_m^* are presented in my poster. During the derivation of Eq. (1) it is crucial to regard the process of insertion or removal of a wall as a legitimate thermodynamic process. Secondly, we find that the indistinguishability of quantum identical particles manifest itself in the low temperature; One can extract more work from the bosonic SZE but less work from the fermionic SZE.

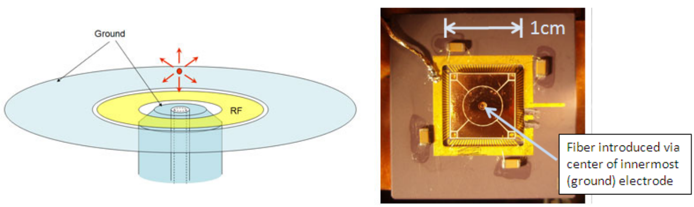
Optical fiber integrated point Paul trap

T.H. Kim[1], P.F. Herskind[1], T.H. Kim[2], J.S. Kim[2], I.L. Chuang[1]

[1] *Center for Ultracold Atoms, MIT, Cambridge, MA*
[2] *Department of Electrical and Computer Engineering, Duke University, Durham, NC*

Surface-electrode ion traps represent a distinct advance in quantum information processing, in that the trap manufacturing process inherits the inherent scalability associated with conventional microfabrication. However, the construction of large-scale ion processors will require not only a sensibly scalable electrode architecture for trapping many ions simultaneously, but also additional infastructure for optical readout and control of the many ion qubits.

We report on progress towards an optical fiber-integrated planar trap for the purpose of ion control. The design (see Figure 1) is based on a novel type of surface trap with cylindrically symmetric arrangement of the electrodes, known as the "point Paul" trap. This particular layout lends itself well to integration with optical fibers and other optical structures, many of which possess symmetry about an axis. In addition, the point Paul design allows dynamic control of ion height (typical variations of $\pm 40\%$) by applying a second RF to the innermost electrode, thereby varying the fiber-ion coupling. The current implementation is based on a 3um-core fiber that is single-mode for both the doppler cooling (422nm) and the qubit (674nm) transitions of strontium. The ion is held 1mm away from the trap plane, at which the laser spot sizes are 45um and 72um for the 422nm and 674nm transitions, respectively. We have deployed the trap in a 4K closed-cycle cryostat and have stably trapped ions with the fiber-integrated structure. Furthermore, both axial and radial trap frequencies were measured that agree with simulation, and ion overlap with the fiber-introduced 674nm light was demonstrated by observing shelving (during $5S_{1/2} \leftrightarrow 5P_{1/2}$ doppler cooling) into the dark $4D_{5/2}$ state.



(a) (b)

Figure 1: *(a) Schematic of the fiber-integrated point Paul trap. The ground electrode is fabricated on an off-the-shelf optical ferrule. (b) Photograph of the actual assembly.*

The point Paul design represents a trap primitive with optical integration in mind, which is a necessity in the construction of large-scale ion trap processors. Furthermore, with its capability for *in situ* ion height adjustment, the trap be may immediately useful in investigation of surface effects, such as anomalous ion heating which currently impedes progress in quantum computation with trapped ions.

Progress with initialization, readout and entanglement of barium ion qubits

N. Kurz, G. Shu, M. R. Dietrich, T. Noel, B. B. Blinov

University of Washington, Seattle, WA United States

Barium ions represent an ideal candidate for ionic qubits with the longest wavelength cooling transitions of any hydrogen-like ion, a long-lived D-state for shelving readout and high isotopic abundance for both the spinless 138 and nuclear spin $I = 3/2$ 137 isotopes. In $^{137}\mathrm{Ba}^+$, we have demonstrated optical Rabi oscillations at 1.762 nm on the $6\mathrm{S}_{1/2}$ to $5\mathrm{D}_{5/2}$ transition as well as microwave oscillations at 8.037 GHz between the $F = 1$, $m_F = 0$ and $F = 2$, $m_F = 0$ levels of the ground state, the former with a decay of $120\mu s$ and the latter unresolved after $800\mu s$[1]. Because neither of these schemes possesses a unique coupling to emitted photon modes, we have begun work to demonstrate Rabi rotations between the Zeeman levels of the ground state of $^{138}\mathrm{Ba}^+$ in a weak magnetic field.

State of the art fluorescence collection techniques with refractive optics limit the solid angle of photon collection to a few percent at most. We have incorporated a spherical mirror with a linear Paul trap to subtend 1.24 sr of solid angle (or about 10% of 4π) with downstream correction of non-paraxial rays[2]. Recently, we have demonstrated a working trap where the linear RF electrodes have been replaced by the metallic surface of a small spherical mirror, which has demonstrated a 1.5-fold increase in fluorescence collection over the previous design, even without correction. This new design has the potential to enable a diffraction-limited focus suitable for high-efficiency fiber coupling. Near unit effiency excitation with a mode-locked laser has been demonstrated on the $6\mathrm{S}_{1/2} \rightarrow 6\mathrm{P}_{3/2}$ transition[3], as well as the generation of single photons as confirmed with a $g^{(2)}$ correlation measurement. These two developments, along with the long wavelength of the barium ion's fluorescence which transmits with low attenuation in optical fiber will potentially lead to higher efficiency in the generation of entangled ion pairs.

Continuing work focuses on extending our single qubit work to couple ionic qubits and the further improvement of efficiency in all steps of the computation process. Projects include the addition of an FPGA-based pulse programmer for generation of pulses with arbitrary shape, frequency and inter- and intra-channel phase, investigating the development of an OPO-based system to increase 1.762 nm power to a watt to improve readout speed and an interferometer for partial Bell state analysis of photons to generate remotely entangled ion pairs. This last is a crucial step for loophole-free Bell tests and quantum repeater protocols.

[1] M. R. Dietrich, et. al., "Hyperfine and Optical Barium Ion Qubits," Phys. Rev. A **81**, 052328 (2010).

[2] G. Shu, et. al., "Efficient fluorescence collection from trapped ions with an integrated spherical mirror", Phys. Rev. A **81**, 042321 (2010).

[3] N. Kurz, et. al., "Precision measurement of the branching ratio in the $6\mathrm{P}_{3/2}$ decay of BaII with a single trapped ion", Phys. Rev. A **77** 060501(R) (2008).

Cavity-Based High-Fidelity and Energy-Exchange-Free Readout of a Neutral Atom Qubit

Roger Gehr, Jürgen Volz, Guilhem Dubois, Jérôme Estève, Jakob Reichel

Laboratoire Kastler-Brossel, ENS, CNRS, UPMC, 24 rue Lhomond, 75005 Paris, France

We prepare and detect the hyperfine state of a single ^{87}Rb atom coupled to a fiber-based high-finesse cavity on an atomchip. The atom is extracted from a Bose-Einstein condensate and trapped at the maximum of the cavity field, resulting in a reproducibly strong atom-cavity coupling. The cavity reflection and transimission signals allow us to detect the atomic hyperfine state with a fidelity above 99.92 % in a readout time of 100 μs without losing the atom[1].

We also measure the atomic spontaneous emission rate during detection and show that most of the information on the atomic state is carried by photons leaving the cavity without having been scattered by the atom. Our measurement apparatus detects a significant fraction of this information, thereby performing a highly efficient qubit readout that is far in the energy-exchange-free measurement regime. We observe one order of magnitude less scattering than possible in an ideal free-space detection scheme with the same fidelity.

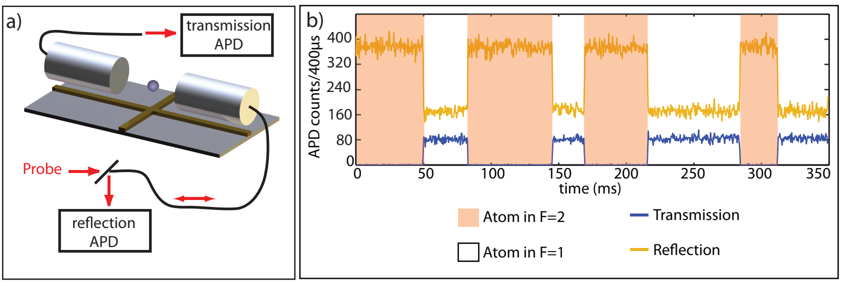


Figure 1: *a) Experimental setup. A single atom is coupled to a fiber-based high-finesse cavity on an atomchip. b) Cavity transmission and reflection signals with a single atom performing quantum jumps between hyperfine states F=2 and F=1. The high contrast is used for efficient and high-fidelity state readout.*

[1] R. Gehr, J. Volz, G. Dubois, T. Steinmetz, Y. Colombe, B.L. Lev, R. Long, J. Estève, J. Reichel, Phys. Rev. Lett. **104**, 203602 (2010).

Photonic Phase Gate via an Exchange of Fermionic Spin Waves in a Spin Chain

A.V. Gorshkov[1], J. Otterbach[2], E. Demler[1], M. Fleischhauer[2], M.D. Lukin[1]

[1] *Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Department of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663, Kaiserslautern, Germany*

We propose[1] a new protocol for implementing the two-qubit photonic phase gate. In our approach, the π phase is acquired by mapping two single photons into atomic excitations with fermionic character and exchanging their positions. The fermionic excitations are realized as spin waves in a spin chain, while photon storage techniques provide the interface between the photons and the spin waves. Possible imperfections and experimental systems suitable for implementing the gate are discussed.

[1] A.V. Gorshkov, J. Otterbach, E. Demler, M. Fleischhauer, arXiv:1001.0968 [quant-ph].

The Dicke quantum phase transition with a superfluid gas in an optical cavity

Christine Guerlin[1,2], Kristian Baumann[1], Ferdinand Brennecke[1], Silvan Leinß[1], Rafael Mottl[1], Tilman Esslinger[1]

[1]*Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland*
[2]*Thales Research and Technology, Campus Polytechnique, 1 Avenue Augustin Fresnel, F-91767 Palaiseau, France*

A phase transition describes the sudden change of state in a physical system, such as the transition between fluid and solid. Quantum gases provide the opportunity to establish a direct link between experiment and generic models which capture the underlying physics. A fundamental concept to describe the collective matter-light interaction is the Dicke model which has been predicted to show an intriguing quantum phase transition. We have realized the Dicke quantum phase transition in an open system formed by a Bose-Einstein condensate coupled to an optical cavity, and have observed the emergence of a self-organized supersolid phase[1]. The phase transition is driven by infinitely long-ranged interactions between the condensed atoms, which are induced by two-photon processes involving the cavity mode and a pump field. We have shown that the phase transition is described by the Dicke Hamiltonian, including counter-rotating coupling terms, and that the supersolid phase is associated with a spontaneously broken spatial symmetry. The boundary of the phase transition is mapped out in quantitative agreement with the Dicke model (see Fig. 1).

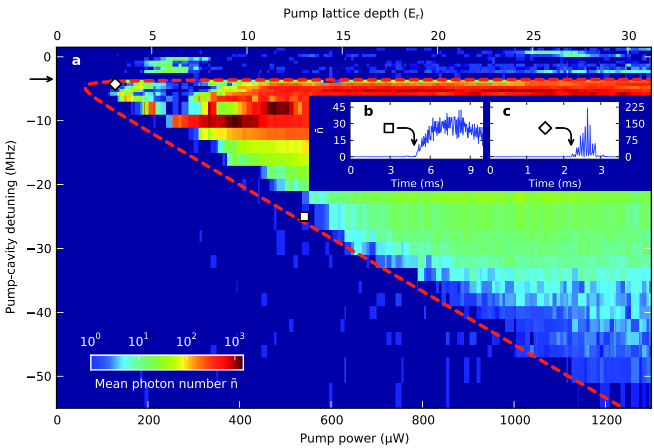


Figure 1: *Phase diagram of the self-organized atom-cavity system*

[1]K. Baumann, G. Guerlin, F. Brennecke and T. Esslinger, Nature **464**, 1301 (2010)

Quantum Hall physics with photonics

Mohammad Hafezi[1], Eugene Demler[2], Mikhail Lukin[2], Jacob Taylor[1]

[1] *Joint Quantum Institute, University of Maryland and NIST, College Park, MD 20742, USA*

[2] *Physics Department, Harvard University, Cambridge, MA 02138, USA*

Particles in two-dimensional structures with a magnetic field exhibit a remarkable variety of macroscopic quantum phenomena, including integer and fractional quantum Hall and quantum spin Hall effects, and prediction regimes of fractional or non-abelian statistics. While electronic systems have been the focus of experiments, theoretically these effects can occur with bosons. Potential bosonic systems include ultra-cold gases and also more recently, photons. Using photons presents a unique set of opportunities and challenges, as to date breaking the time-reversal symmetry and simulating the magnetic field has been hampered by technical challenges. In this work, we circumvent these challenges by resorting to a time-reversal invariant scheme, in an analogy to electronic spin-orbit mechanism which plays a similar role to the magnetic field. We show how simple arrays of coupled optical resonators can simulate various quantum Hall physics models. Furthermore, by appropriate choice of probe and reflective elements, either quantum Hall or quantum spin Hall physics may be explored. This approach appears feasible with current technology and operates at room temperature, and paves the way for detailed observations of bosonic quantum Hall physics and its potential application in photonics.

Single atom-single photon coupling in free space

G. Hétet[1,2], L. Slodička[1], S. Gerber[1], M. Hennrich[1], R. Blatt[1,2]

[1]*Institute for Experimental Physics, University of Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria*
[2]*Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, Austria*

Our work aims at enhancing the magnitude of single-photon single-atom interactions using an ion trap apparatus and high numerical aperture (NA) optics to carry out fundamental investigations on quantum electro-dynamics and information processing with single atoms. Coupling of radiation to a single atom in free space is generally considered to be weak, however, technological advances, as nowadays available with large aperture lenses and mirrors, recently led to reconsider this point of view.

We first present an experimental demonstration of Electromagnetically Induced Transparency (EIT) of a tightly focussed probe from a single trapped ion[1]. Figure 1 shows the transmission of a weak probe field through a single atom as a function of the dressing laser frequency in a lambda-type three level atom. Here, the ion acts as a mirror with tunable reflection for weak incident light fields.

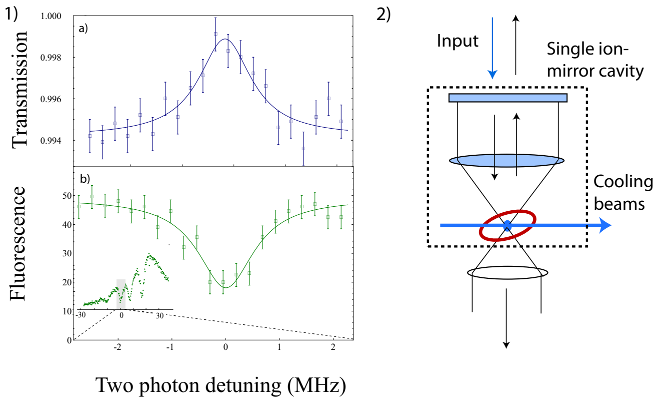


Figure : *1- a) EIT spectrum from a single trapped ion, b) Emitted fluorescence. 2) Sketch of the single-ion single-mirror Fabry-Pérot cavity.*

We also demonstrate a novel Fabry-Pérot cavity made of single ion and a single mirror. Such a set-up is depicted Figure 2. Although only few reflexions are observed in our set-up, this system can behave as a high finesse cavity in the limit of large numerical aperture, and can be readily extended to a cavity with only two ions as the input and ouput mirrors.

[1]Slodička et al. arXiv:1005.3289 (2010)

Cold atoms inside a hollow core photonic crystal fiber

S. Hofferberth[1], T. Peyronel[2], Q. Liang[2], S. Magkiriadou[1], A.S. Zibrov[1], V. Vuletic[2], M.D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA, USA*
[2]*Department of Physics, MIT, Cambridge, MA, USA*

Typically, interactions of light beams in nonlinear media are very weak at low light levels. Strong interactions between few-photon pulses require a combination of large optical nonlinearity, long interaction time, low photon loss, and tight confinement of the light beams.

Here, we present an approach to overcome these issues that makes use of an optically dense medium containing a few thousand cold atoms trapped inside the hollow core of a photonic crystal fiber. This allows for confinement of both atoms and photons to a transverse size of just a few wavelengths, resulting in high electric field intensity per photon and large optical depths with very small number of atoms. On the other hand, due to the guiding of the light by the fiber the longitudinal interaction length of atoms and photons is not limited by diffraction.

We demonstrate a very efficient all-optical switch, where the transmission of few-photon probe pulses throuh the atomic medium inside the fiber is turned off by the presense of as few as 500 switch photons. We also show results of recent experiments using stationary light pulses and slowed switch photons to further enhance the nonlinearities in the system.

Quantum interference of spontaneous emission from a V-type three-level atom embedded in a photonic crystal

Chih-hsien Huang[1], Jing-Nuo Wu[2], Wen-Feng Hsieh[1,3] Szu-Cheng Cheng[2]

[1]*National Cheng Kung University, Tainan, Taiwan*
[2]*Chinese Culture University, Taipei, Taiwan*
[3]*National Chiao Tung University, Hsinchu, Taiwan*

Fractional calculus is used to study the spontaneous emission of a V-type three-level atom, energy diagram shown in Fig. 1(a), embedded in a photonic crystal with isotropic band structure. Although this system has been addressed by others in the past, the fractional calculus is more correct and provides theoretical results qualitatively fully consistent with the experimental observations because it avoids the complicated complex integrals and the multi-value problem.[1] As detuning these two allowed atomic transition energy, ω_{1c} and ω_{2c}, with respect to the photonic band edge, ω_c, the quantum interference in this atom-field system leads to the splitting of the energy levels into four regimes, namely (I) anti-trapping, (II) population non-inversion, (III) enhanced population, and (IV) enhanced periodic oscillation. The population of these dressed states will decay rapidly in the anti-trapping regime due to the nature of complex eigenfrequencies of the dressed states, whereas, in other regimes, the dressed states last for long period of time. The quantum interference occurs only when more than two dressed states having pure real eigenfrequencies and the visibility of interference is determined by the initial amplitudes of the real-frequency dressed states.

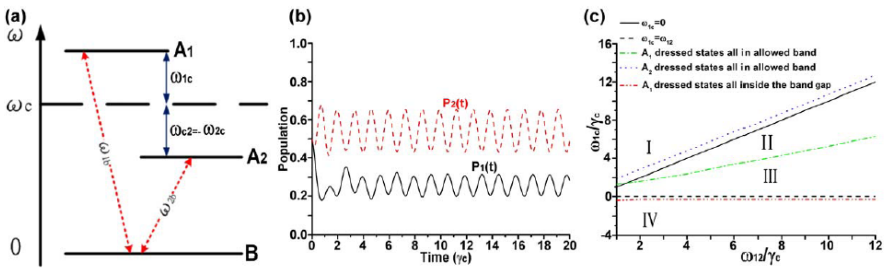


Figure 1: *(a) A three-level atom in a photonic band gap structure. The two excited states ($|A_1\rangle$ and $|A_2\rangle$) are placed around the band gap edge. $|B\rangle$ is the ground state. (b) Atomic populations of the excited states in enhanced periodic oscillation regime, where $P_1(t) = |A_1(t)|^2$ for the upper excited state, $P_2(t) = |A_2(t)|^2$ for the lower excited state. (c) Four regimes of the dressed states, where γ_c is a constant.*

[1]J.N. Wu, C. H. Huang, S. C. Cheng, and W.F. Hsieh, Phy. Rev. A **81**(2), 023827 (2010)

Analytic model for the effects of absorption on relative intensity squeezing

M. Jasperse[1,2], R. E. Scholten[1]

[1]*ARC Centre of Excellence for Coherent X-Ray Science, University of Melbourne, Victoria 3010, Australia*
[2]*School of Physics, Monash University, Victoria 3800, Australia*

Relative intensity squeezing by four-wave mixing in rubidium vapour is a promising tool for performing high precision measurements, with up to 9.2 ± 0.5 dB of measured noise reduction below the shot-noise limit.[1] The technique extends both to the low noise-frequency domain[2] and to multimode beams.[3]

However, a hot vapour is required for strong mixing, leading to Doppler-broadened absorption of the near-resonant beams. Such optical losses destroy quantum correlations and degrade the overall degree of squeezing. Optimising the squeezing process therefore requires balancing the improved mixing and increased absorption close to resonance.

We present a novel model of the simultaneous processes of four-wave mixing gain and Doppler-broadened absorption within the atomic vapour cell. We find analytic expressions for the degree of squeezing expected from the system as a function of the gain and loss coefficients. The model is used to quantify the degree of absorption and mixing observed in experiment, and estimate the limit of achievable squeezing.

Our operator analysis technique is not limited to four-wave mixing systems, and can be applied to other quantum optical systems to quantify the effects of competing absorption processes.

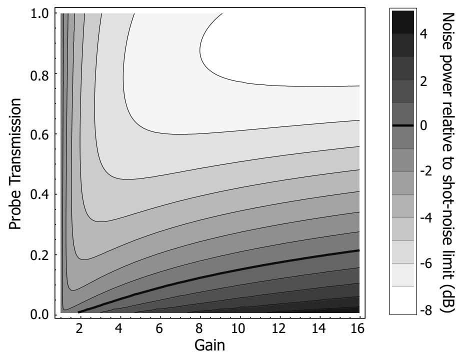


Figure 1: *Predicted relative intensity squeezing as a function of four-wave mixing gain and probe transmission.*

[1]Q. Glorieux, L. Guidoni, S. Guibal, J.-P. Likforman, T. Coudreau. Strong quantum correlations in four wave mixing in ^{85}Rb vapor. `arXiv:1004.3950v1 [quant-ph]` (2010).

[2]C. F. McCormick, A. M. Marino, V. Boyer, and P. D. Lett. Strong low-frequency quantum correlations from a four-wave-mixing amplifier. *Phys. Rev. A*, **78**, 043816 (2008).

[3]V. Boyer, A. M. Marino, R. C. Pooser, and P. D. Lett. Entangled images from four-wave mixing. *Science*, **321** (5888), 544 (2008).

Nondispersive optics using storage of light

Leon Karpa, Martin Weitz

Institut für Angewandte Physik, Universität Bonn, Germany

Electromagnetically induced transparency (EIT) is a quantum interference effect that allows to render otherwise opaque atomic media transparent[1]. Destructive interference of absorption amplitudes here allows for a suppression of optical absorption. Media prepared under the conditions of electromagnetically induced transparency have interesting properties, as an extreme reduction of the optical group velocity[2]. More recently, spatially resolved EIT has been demonstrated, and in two experiments the storage of images has been reported[3,4].
Here we demonstrate the nondispersive deflection of an optical beam in a nonuniform magnetic field. An optical pulse is initially stored as a spin-wave coherence in thermal rubidium vapour. An inhomogeneous magnetic field imprints a phase gradient onto the spin wave, which upon reacceleration of the optical pulse leads to an angular deflection of the retrieved beam. We show that the obtained beam deflection is non-dispersive, i.e. its magnitude is independent of the incident optical frequency. Compared to a Stern-Gerlach experiment carried out with propagating light under the conditions of electromagnetically induced transparency [5], the estimated suppression of the chromatic aberration reaches 10 orders of magnitude[6].

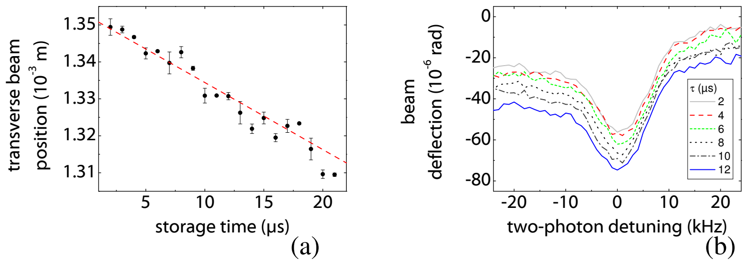


Figure 1: *(a) Measured signal beam position after retrieval as a function of the storage time for a two-photon detuning of $\delta \cong 0$ in the beam center. The points give the average position values determined in four measurement sessions, each acquiring the average of the results of 100 subsequent position measurements. The shown error bars were determined from the standard deviation of the results of the independent sessions. The data points have been fitted with a linear function, as shown by the dashed red line. (b) Deflection of the retrieved signal beam versus the two-photon detuning for different values of the storage duration.*

[1] see e.g.: M. Fleischhauer, A. Imamoglu, and J.P. Marangos, Rev. Mod. Phys. **77**, 633 (2005).
[2] see e.g.: L. V. Hau, S. E. Harris, Z. Dutton, and C.H. Behroozi, Nature (London) **397**, 594 (1999).
[3] M. Shuker, O. Firstenberg, R. Pugatch, A.Ron, and N.Davidson, Phys. Rev. Lett., **100**, 223601 (2008).
[4] P. K. Vudyasetu, R. M. Camacho, and J. C. Howell, Phys. Rev. Lett., **100**, 123903 (2008).
[5] L. Karpa and M. Weitz, Nature Physics **2**, 332 (2006).
[6] L. Karpa and M. Weitz, Phys. Rev. A. **81**, 041802(R) (2010).

How to Detect Photons with $> 99\%$ Efficiency, Not

P.G. Kwiat[1], O. Hosten[1,2]

[1] *University of Illinois at Urbana-Champaign, Urbana, IL, United States*
[2] *Stanford University, Stanford, CA, United States*

Near-perfect efficiency and photon-number resolution (PNR) capability of photon detectors have enormous potential pay-offs in quantum information (QI) technologies and more generally in optical metrology. A prime example is the capability to perform loophole-free tests of violations of Bell inequalities to reveal the nonlocality of quantum mechanics. Other examples encompass optical quantum computing and long distance quantum communication since they would be nearly impossible to achieve without high-efficiency single-photon detectors, as the joint detection probability decreases exponentially with the increasing number of photons. PNR capability (enhancing virtually every quantum communication protocol) is critical for realizing efficient heralded sources of single photons, and could enable the preparation of many-photon entangled states for use in schemes such as quantum lithography or super-resolution interferometry.

Conventional single-photon detectors, like avalanche photodiodes and photo-multiplier tubes, are limited to $< 70\%$ intrinsic detector efficiency, and lack appreciable PNR capabilities. State of the art detectors (with PNR) such as visible light photon counters (VLPCs) and superconducting transition-edge sensors are limited to system efficiencies of $\sim 88\%$ and $\sim 95\%$ respectively.

A novel non-solid-state approach based on photo-detection via atomic vapors to building PNR detectors with expected efficiencies above 99% was proposed in references [1, 2] (Fig. 1). An incident photon – in conjunction with a strong escort beam – excites one atom in an ensemble to a metastable state $|s>$; this is then detected by means of a high-efficiency cycling transition. In this contribution we will present an investigation of the feasibility of the atomic-vapor-based detectors. In particular, we will explore the challenges that could prevent these detectors from operating at the envisioned level of $> 99\%$, and propose alternative solutions.

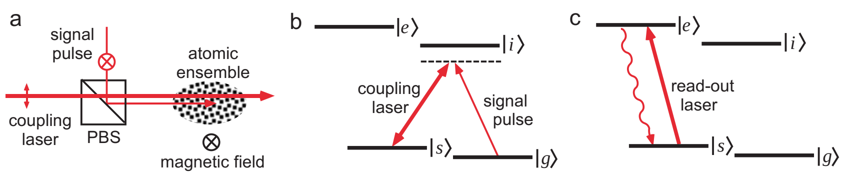


Figure 1: *Schematic of an atomic-vapor based photon detector. a, The configuration. PBS: Polarizing beam-splitter. b, Controlled absorption step. c, Fluorescence read-out step; the read-out laser (not shown) travels perpendicular to the plane of the page.*

[1] D. F. V. James and P. G. Kwiat, "Atomic vapor-based high efficiency optical detectors with photon number resolution", Phys. Rev. Lett. 89, 183601 (2002).

[2] A. Imamoglu, "High Efficiency Photon Counting Using Stored Light", Phys. Rev. Lett. 89, 163602 (2002).

A single-interaction step implementation of a quantum search in coupled micro-cavities

E.S. Kyoseva[1], D.G. Angelakis[1,2], L.C. Kwek[1]

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

We present a method for realizing efficiently Grover's search algorithm [1] in an array of N coupled cavities doped with three-level atoms. To realize a physical implementation of a quantum algorithm, it is important that one can encode the basic units of quantum information, i.e. the qubits, initialize them to some suitable inputs, perform an adequate set of unitary operations and then finally read the output.

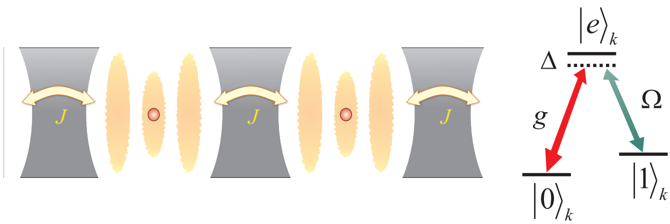


Figure 1: *An array of coupled cavities via hopping photons between neighbouring sites at a rate J doped with three-level atomic lambda systems.*

Here we show how those basic building operations can be performed in an *efficient* way for a system of coupled cavities [2]. We start by noting that the basic Grover iteration is executed in two steps – first, the oracle O is applied to mark the searched state by flipping its phase, and then a global reflection operation about the mean $\mathcal{G}(W) = 1 - 2|W\rangle\langle W|$ is performed, where W is the N-qubit W state. We show that by the application of appropriately tuned global laser fields and exploiting the natural evolution of our system we can implement the N-qubit reflection operation $\mathcal{G}(W)$ – also known as a quantum mirror or Householder reflection [3] – in only *one physical step*. Thus, the time steps in which Grover's search can be implemented become equal to the mathematical steps $\sim \mathcal{O}(\sqrt{N})$, which is a considerable improvement compared to existing schemes which require $\sim \mathcal{O}(N^2)$. We study the robustness of the implementation against errors due to photon loss and fluctuations in the cavity frequencies and atom-photon coupling constants.

[1]L.K. Grover, Physical Review Letters **79**, 325 (1997).
[2]E.S. Kyoseva, D.G. Angelakis, and L.C. Kwek, Europhysics Letters **89**, 20005 (2010).
[3]A.S. Householder, J. ACM **5**, 339 (1958).

Generation of tunable second order coherence classical light

H.J. Lee, H.S. Moon

Department of Physics, Pusan National University, Busan, Korea

Second order coherence, $g^{(2)}(\tau)$ is one of concepts of light that could distinguish classical and quantum prediction, therefore lead to an alternative threefold classification in which the light is described as antibunced, coherent, bunched [1]. As is well known, $g^{(2)}(0)$ of a laser and a thermal light is 1 and 2, respectively [2]. However, the coherence of a general thermal light is too short to obtain right information through electronic device in present, so researchers used pseudo-thermal light that can simulate the behavior of true thermal light [3]. In this study, we experimentally demonstrated the tunable second order coherence (TSOC) classical light by a mixture of a laser and a pseudo-thermal light [4]. We focused on the behavior of mixed light that has $g^{(2)}(0)$ between 1 and 2. The simple method for generation of the TSOC classical light represents a mixture of a laser and a pseudo-thermal light adjusting to the photon number ratio of two light sources. The laser source is the distributed feedback (DFB) laser with single mode operation in 795 nm. The pseudo-thermal light with approximately $g^{(2)}(0) = 1.8$ was generated from the DFB laser passed through the rotating opaque plastic plate. Figure 1(a) shows the experimental result measured $g^{(2)}(0)$ of the TSOC classical light according to the photon number ratio of pseudo-thermal light. Figure 1 (b) shows the calculated $g^{(2)}(0)$ of the mixed light summed the coherent light with the Poisson distribution and the chaotic light with the Bose-Einstein distribution. $g^{(2)}(0)$ of the TSOC classical light was arbitrarily controlled between 1 and 1.8. There was good qualitative agreement between theoretical and experimental results.

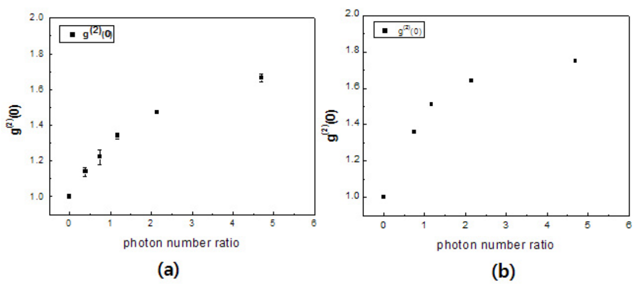


Figure 1: $g^{(2)}(0)$ *measurement of TSOC classical light; (a) experimental results, (b) theoretical results.*

[1] R. Hanbury-Brown and R.Q. Twiss, Nature 177, 27 (1956)
[2] R. J. Glauber, Phys. Rev. 131, 2766 (1963)
[3] P. Koczyk, P. Wiewior, and C. Radzewicz, Am.J. Phys. 64, 3, (1996)
[4] F. T. Arecchi, A. Berne, A. Sona, and P. Burlamacchi, IEEE Journ. Quantum Electronics 2, 341 (1966)

Quasieigenstate Coalescence at the Exceptional Point in a Coupled Atom-Cavity System

S. Lim[1], Y. Choi[2], S. Kang[1], W. Kim[1], J.-R. Kim[1], J.-H. Lee[1], and K. An[1]

[1]*Department of Physics and Astronomy, Seoul National University, Seoul, Korea*
[2]*Department of Physics, Korea University, Seoul, Korea*

When a quantum system has energy dissipation, its dynamics is described by a non-Hermitian Hamiltonian. There can be exceptional points(EP)[1] in the parameter space of the system at which two or more quasieigenstates coalesce into one. The experiment for EP had been mainly performed in classical systems composed of interacting cavity modes though theoretical studies have been made in various systems. We have observed an EP in a coupled atom-cavity system, a full quantum composite.[2] In our experiment, we have $(g_0, \kappa, \gamma)/2\pi = (11.1, 21.0, 3.0)$MHz, where g_0 is a maximum coupling constant, κ is the cavity decay rate and γ is the decay rate of a ^{85}Rb atom. The interaction between a single atom and a cavity mode was observed by monitoring the transmission of a cavity probe beam. Because of the multi-level structure of ^{85}Rb atom, the effective atomic dipole moment can be changed by the ellipticity of the probe laser polarization with a result of continuous control on the coupling constant[3]. Varying the atom cavity detuning Δ_{ac} and the coupling constants g around an EP $(g = (\kappa - \gamma)/2, \Delta_{ac} = 0)$, we obtained the transmission spectrum of the system. As a result, the transition from avoided level crossing to level crossing, 4π rotational symmetry and the critical behavior in resonance cavity transmission were observed.

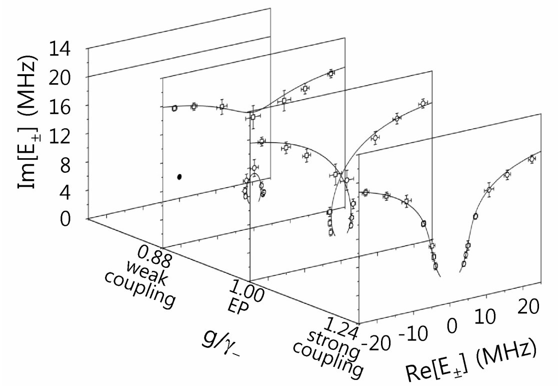


Figure 1: *Complex eigenenergy trajectories for various coupling constant and the atom-cavity detuning.*[2] *Two trajectories are crossed at the EP.*

[1]T. Kato, *Perturbation Theory for Linear Operators* (Springer, New York, 1966).
[2]Y. Choi, S. Kang, S. Lim, W. Kim, J.-R. Kim, J.-H. Lee, and K. An, Phys. Rev. Lett. **104**, 153601 (2010).
[3]S. Kang, Y. Choi, S. Lim, W. Kim, J.-R. Kim, J.-H. Lee, and K. An, Optics Express **18**, 9286 (2010).

A Subwavelength Optical Lattice using Surface Plasmons

M. Gullans[1], D.E. Chang[2], J.D. Thompson[1], J.I. Cirac[3], and M.D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Center for the Physics of Information and Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125, USA*
[3]*Max-Planck-Institut fr Quantenoptik, Hans-Kopfermann-Strasse 1, Garching, D-85748, Germany*

We discuss a scheme for generating an optical lattice by illuminating a two-dimensional array of metallic nanospheres near their surface plasmon resonance. The lattice spacing is set by the spacing between adjacent spheres and can be much smaller than a wavelength for small enough spheres. The depth of the lattice can be tuned by changing the polarization of the incoming light, which allows an adiabatic loading procedure based on a slow rotation of the polarization. We estimate the trap lifetime including the van der Waals attraction with the sphere. Finally, we discuss several potential applications for quantum simulation with this system.

Simulation of a quantum phase transition of polaritons with trapped ions

P. A. Ivanov[1,2], S. S. Ivanov[2], N. V. Vitanov[2], A. Mering[3], M. Fleischhauer[3], K. Singer[1]

[1] *Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[2] *Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria*
[3] *Fachbereich Physik, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*

We present a novel system for the simulation of quantum phase transitions of collective internal qubit and phononic states with a linear crystal of trapped ions. The laser-ion interaction creates an energy gap in the excitation spectrum, which induces an effective phonon-phonon repulsion and a Jaynes-Cummings-Hubbard interaction. This system shows features equivalent to phase transitions of polaritons in coupled cavity arrays. Trapped ions allow for easy tuning of the hopping frequency by adjusting the axial trapping frequency, and the phonon-phonon repulsion via laser detuning and intensity. We propose an experimental protocol to access all observables of the system, which allows one to obtain signatures of the quantum phase transitions even with a small number of ions.

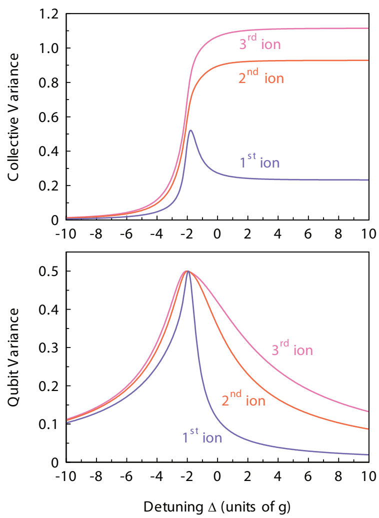


Figure 1: *Total (qubit+phonon) variance $\mathcal{D}N_k$ (top) and the qubit variances $\mathcal{D}N_{a,k}$ ($k = 1, 2, 3$) (bottom) for a chain of five ions with five excitations as a function of the laser detuning Δ for fixed hopping $t = 0.3g$. Negative values of Δ correspond to blue detuning with respect to the red-sideband transition.*

Equilibrium and out-of-equilibrium properties of ultracold fermions in optical lattices

R. Jördens, L. Tarruell, D. Greif, T. Uehlinger, N. Strohmaier, H. Moritz, and T. Esslinger

Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland

We present the results of a combined experimental and theoretical study of repulsively interacting ^{40}K atoms in the Hubbard model. Accurate measurements of the double occupancy provide direct access to the system's properties both in equilibrium and in the linear response regime. By calibrating the equilibrium double occupancy against theoretical models over a wide range of parameters we develop a reliable measure for the entropy in the lattice. We demonstrate the applicability of both high-temperature series and dynamical mean field theory to obtain quantitative agreement with the experimental data.

Additionally, we perform weak lattice modulation and monitor the increase of doublons with time. The observations are well captured by linear response theory and are sensitive to local spin ordering, which can be used to detect antiferromagnetic states. For long modulation times the system is driven into a far-from-equilibrium state with many additional doublons. We show that the dominant decay mechanism is a high-order scattering process and the doublon lifetime depends exponentially on the ratio of onsite interaction to tunneling energy.

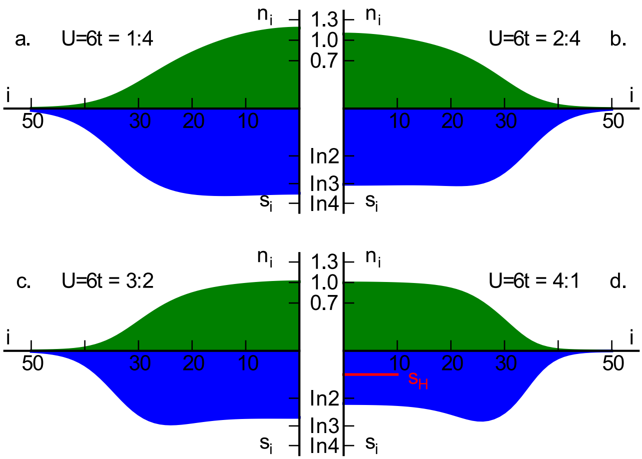


Figure 1: *Particle number and entropy of fermionic atoms in an optical lattice.*

Simulating quantum effects of cosmological expansion using a static ion trap

N. C. Menicucci[1], S. J. Olson[2], G. J. Milburn[2]

[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[2]*Centre for Quantum Computer Technology, School of Mathematics and Physics, The University of Queensland, St Lucia, QLD, 4072, Australia*

We propose a new experimental testbed that uses ions in the collective ground state of a static trap for studying the analog of quantum-field effects in cosmological spacetimes. To date, proposals for using trapped ions in analog gravity experiments have simulated the effect of gravity on the field modes by directly manipulating the ions' motion.[1] In contrast, by associating laboratory time with *conformal time* in the simulated universe, we can encode the full effect of curvature in the modulation of the laser used to couple the ions' vibrational motion and electronic states; this modulated coupling serves as the analog of a field detector in an expanding spacetime.

Curved-spacetime quantum field theory (QFT) is essential to cosmology[2] and has given rise to fascinating results such as black-hole evaporation.[3] The difficulty in testing these effects directly has given rise to a number of proposals for testing *analog* curved-spacetime QFT effects,[4] where spacetime is replaced by a laboratory system of coupled atoms (either individual atoms or a quasi-continuous fluid), and field modes are replaced by the collective modes of oscillation of the atoms—effectively a "phonon field." While the observable effects are conceptually the same (analogous), the parameters of the experiment may be adjusted to result in a much stronger and more easily observed effect.

In the current proposal, the collective ground state of ions in a static linear trap serves as the analog of a scalar field in the conformal vacuum (i.e., the ordinary Minkowski vacuum with the ordinary time coordinate replaced by conformal time), and we encode the effects of spacetime curvature into a modulation of the analog detectors (i.e., the coupling of electronic and vibrational motion of a single ion), rather than in the motion of the atoms which comprise the analog spacetime. This amounts to making a shift in the analogy away from *laboratory time* $\leftrightarrow$ *detector proper time* and towards *laboratory time* $\leftrightarrow$ *conformal time*. For many useful cases studied in cosmology, this identification encodes the entire effect of the spacetime curvature and therefore enables us to propose analog curved-spacetime QFT experiments in which the analog spacetime is fixed, thus making our proposals far more accessible experimentally. Further details may be found in arXiv:1005.0434 [quant-ph].

---

[1]P. M. Alsing, J. P. Dowling, and G. J. Milburn, "Ion Trap Simulations of Quantum Fields in an Expanding Universe," Phys. Rev. Lett. **94**, 220401 (2005); R. Schützhold *et al.*, "Analogue of Cosmological Particle Creation in an Ion Trap," Phys. Rev. Lett. **99**, 201301 (2007).
[2]S. Weinberg, *Cosmology* (Oxford University Press, 2008).
[3]S. Hawking, "Particle creation by black holes," Commun. Math. Phys. **43**, 199 (1975).
[4]W. G. Unruh, "Experimental Black-Hole Evaporation?" Phys. Rev. Lett. **46**, 1351 (1981).

The FERRUM project: laboratory-measured transition probabilities for Cr II

J. Gurell[1], H. Nilsson[2], L. Engström[3], H. Lundberg[3], R. Blackwell-Whitehead[2], K.E. Nielsen[4,5], S. Mannervik[1]

[1]*Department of Physics, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden*
[2]*Lund Observatory, Lund University, Box 43, SE-22100 Lund, Sweden*
[3]*Atomic Physics, Department of Physics, Lund University, Box 118, SE-22100 Lund, Sweden*
[4]*Catholic University of America, Washington, DC 20064, USA*
[5]*Astrophysics Science Division, Code 667, Goddard Space Flight Center, Greenbelt, MD 20771, USA*

Transition probabilities for 145 allowed Cr II lines corresponding to radiative decays from the $z\ ^4\mathrm{H}_J$, $z\ ^2\mathrm{D}_J$, $y\ ^4\mathrm{F}_J$, and $y\ ^4\mathrm{G}_J$ levels with energies between 63000 and 68000 cm^{-1} have been experimentally determined using a combination of lifetime and branching fraction (BF) measurements.

The lifetimes were measured by monitoring time resolved laser induced fluorescence[1] at the Lund High Power Laser Facility and the BFs were determined by line fitting of an intensity calibrated Fourier transform spectrum from a Penning discharge lamp with chromium cathodes recorded at Lund Observatory.

The log(gf)-values were compared with results from the semi-empirical calculations of Kurucz[2] and Raasen & Uylings[3]. Several of the investigated upper levels are close in energy and appear to be severely mixed which complicates the calculations. Nevertheless, the experimental A-values are reasonably well reproduced by the calculations of Raasen & Uylings[3] which also show great agreement with our experimental lifetimes.

[1]Xu, H.L., Svanberg, S., Quinet, P., Garnir, H.P., and Biémont, E. 2003, J. Phys. B: At. Mol. Opt. Phys. 36 4773

[2]Kurucz, R.L. 1988, Trans. IAU, XXB, M. McNally, ed., (Dordrecht:Kluwer), 168

[3]Raasen, A.J.J., and Uylings, P.H.M. 1997, unpublished data available at: ftp://ftp.wins.uva.nl/pub/orth/chromium

Saturation of a transition between two levels in a three-level Λ configuration

Hyok Sang Han, D. Cho

Korea University, Seoul, Korea

Fluorescence line shape of a transition between two levels in a three-level Λ configuration is studied. The transition is saturated due to an optical pumping into the third state. Unlike usual saturation in a two-level system, which is caused by large intensity, the three-level saturation is mainly due to long interaction time. We obtained analytic expression for the fluorescence line shape and verified it using a three-level Λ configuration consisting of $5^2S_{1/2}$ F=2, F=3 and $5^2P_{1/2}$ states of ^{85}Rb. We used an atomic beam from a low-velocity intense source in a pulsed mode. We varied the width of the probe beam to control the interaction time while the probe intensity is kept well below saturation intensity.

As an application of this scheme, a spectroscopic measurement of a branching ratio of an atomic transition is possible. When a transition is saturated, total number of photons scattered by an atom depends only on the branching ratio. We present an experimental scheme to measure the branching ratio.

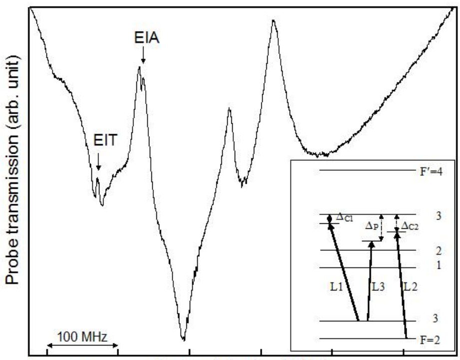
Coherent properties of a multi-level Λ and V-type systems

Md. Mabud Hossain[1], Soma Mitra[1], Biswajit Ray[1,*], Pradip N. Ghosh[2]

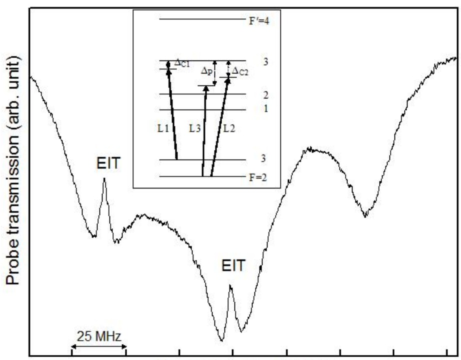
[1]*Dept. of Physics, University of Calcutta, 92, A. P. C. Road, Kolkata-700 009, India*
[2]*Jadavpur University, 188, Raja S. C. Mallik Road, Kolkata-700 032, India*
**email:brphy@caluniv.ac.in*

We study the quantum coherence and interference effects such as coherent population trapping (CPT) [1], electromagnetically induced transparency (EIT) [2] and electromagnetically induced absorption (EIA) [3] in a multi-level Λ and V-type systems of ^{85}Rb-D_2 hyperfine transitions. In a Λ-type system, the EIT formation is obtained due to the interaction of atoms with pump-probe laser fields which produces a superposition state of the ground levels called dark state. In a dark state, the populated atoms are non-absorbing to the probe field and the system becomes transparent which is called EIT. In a V-type system, the EIT formation occurs mainly due to the coherence effect between two optical transition pathways.

In presence of pump (L1) and probe (L3) laser fields, if we apply another frequency controlled laser (L2) field then a combination of Λ and V-type system can be obtained which may produce the EIT and EIA signals simultaneously (Fig. 1). Also the double EIT formation in presence of two control laser fields is shown (Fig. 2) which may be useful in the application of four and six wave mixing processes [4].



(Fig. 1)



(Fig. 2)

Figure 1: *Observed spectrum of simultaneous EIT and EIA signals and the corresponding level scheme.*

Figure 2: *Observed spectrum of double EIT signals and the corresponding level scheme.*

Acknowledgment: This work is supported by UGC through UPE scheme of C.U. and DST, Govt. of India. M.M.H.also acknowledges CSIR for Research Fellowship. [1]

[1]E. Arimondo, Prog. Opt. **35,** 259 (1996).
[2]D. J. Fulton, *et al.* Phys. Rev. A **52,** 2302 (1995).
[3]A. Lezama, *et al.* Phys. Rev. A **59,** 4732 (1999).
[4]Y. Zhang, *et al.* Phys. Rev. Lett. **99,** 123603 (2007).

Hyperfine structure splitting of molecular-iodine transitions near 716 nm

N. Huet[1], S. Krins[1], P. Dubé[2], T. Bastin[1]

[1]*Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, Belgium*

[2]*Frequency and Time Group, Institute for National Measurement Standards, National Research Council of Canada, Ottawa, Canada*

Saturation spectroscopy is a well known technique to get Doppler-free spectral lines of elements at ultra-high resolution. It is also a popular technique to precisely stabilize laser radiation within atomic linewidths. Here we report results about saturated absorption spectra of molecular iodine of the resonance line ${}^3\Pi^+_{0u} \leftarrow {}^1\Sigma^+_g R(90)3 - 10$ at 716 nm. The iodine vapor is produced in a cell with adjustable temperature including a cold finger which allows the control of the pressure. We use a Ti:S laser system with a pump laser at 532 nm. The Ti:S laser beam is first stabilized in intensity with help of a servo loop acting on an acousto-optical modulator. The intensity-stabilized laser beam is then split into a pump and a probe beam. The pump beam is chopped with help of an acousto-optical modulator at a chopping frequency of 5 kHz. The probe beam saturated absorption spectra are recorded with help of the usual lock-in amplifier technique. The spectra of the hyperfine structure of molecular iodine are presented for several transitions around the transition R(90) 3-10 at 716 nm (line 529 in Gerstenkorn atlas[1]). A sample of our spectra is illustrated in Fig. 1.

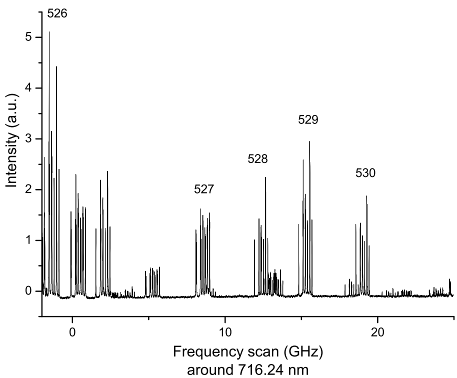


Figure 1: *Hyperfine-structure resolved spectrum of lines 526-530 of Gerstenkorn atlas*[1].

[1]S. Gerstenkorn, J. Verges & J. Chevillard, *Atlas du spectre d'absorption de la molécule diode, 1100- 1400 cm*[1] (Laboratoire Aimé-Cotton, Orsay, France, 1978)

Ultra narrow dark resonance in high temperature caesium cell using mode-locked Ti:sapphire laser and neon buffer gas

G. Imreh, T-H. Wu, C-M. Wu, T-L. Yang, W-Y. Cheng,

Institute of Atomic and Molecular Sciences, Academia Sinica, Taiwan

Dark resonances due to coherent population trapping (CPT) offer naturally narrow line widths and are well suited for frequency standards. The width of these resonances can be reduced by using buffer gas. In continuous wave (CW) systems line width below 30Hz were previously observed in rubidium[1]. For further improvement we use a mode-locked Ti:sapphire laser for optical pumping. This has the advantage of all interacting modes being in phase with each other, while in CW case the phase coherence of the pump lasers limit performance. Our system is unique in that the repetition rate and the offset frequency can be tuned independently [2].

The repetition rate of the mode-locked laser is set to be near an integer multiple of the ground state hyperfine splitting of caesium (the "clock frequency"). By scanning the repetition rate we probe the dark resonance. Compared to previous similar experiments[3] we use a different element and higher buffer gas temperature. In a cell buffered with 8700 kPa neon at 100°C we recorded 6.1(8) Hz line width (Figure 1). The expected large frequency shift of the resonance due to the buffer gas (several kHz) is absent, the observed shift is much smaller than the line width.

An optical clock based on this CPT signal using mode locked lasers will have the advantage of narrower resonance, much reduced systematic frequency shifting effects and due to its higher peak power the ability to use thicker optical medium, achieving better signal-to-noise ratio.

We present our systematic studies of the this CPT signal and its theoretical analysis.

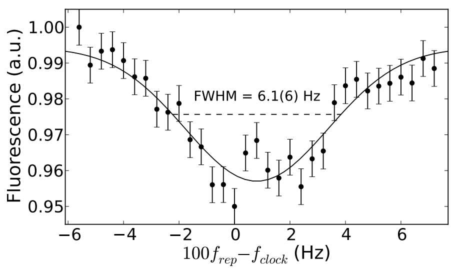


Figure 1: *Dark resonance signal by tuning the mode locked laser's repetition rate*

[1] M. Erhard and H. Helm, PRA **63**, 043813 (2001)

[2] W-Y. Cheng, T-H. Wu, S-W. Huang, S-Y. Lin and C-M. Wu, Applied Physics B **92**, 13 (2008)

[3] S. Brattke, U. Kallmann, and W.-D. Hartmann, Eur. Phys. J. D **3**, 159 (1998)

Spectroscopic analysis of the 1 $^3\Delta_1$, 4 $^1\Sigma^+$, and 5 $^1\Sigma^+$ states of the KRb diatomic molecule using molecular beam experiment

Y. Lee[1], Y. Yoon[2], A. Muhammad[3], J.T. Kim[3], S. Lee[4], B. Kim[2]

[1]*Department of Chemistry, Mokpo National University, Jeonnam 534-729, Korea*
[2]*Department of Chemistry, KAIST, Daejeon 305-701, Korea*
[3]*Department of Photonic Engineering, Chosun University, Gwangju, 501-759, Korea*
[4]*College of Environmental Science and Applied Chemistry, Kyunghee University, Gyeonggi-do 449-701, Korea*

We have investigated the electronic states of the KRb diatomic molecule near 480 nm by mass-resolved resonance enhanced two-photon ionization in a cold molecular beam. The 1 $^3\Delta_1$, 4 $^1\Sigma^+$, and 5 $^1\Sigma^+ \leftarrow X\ ^1\Sigma^+(v"=0, 1)$ states have been identified in that spectral region. For the 1 $^3\Delta_1$, and 5 $^1\Sigma^+$ states, the electronic term values (T_e) and vibrational constants are determined experimentally for the first time. Potential energy curves of the 4 $^1\Sigma^+$ and 5 $^1\Sigma^+$ states undergo multiple avoided crossings with nearby $^1\Sigma^+$ states in the observed spectral region. From a rotational contour analysis, the symmetries of the upper electronic states of the observed bands were assigned. For the 4 $^1\Sigma^+$ state, vibrational numbering of the experimentally observed levels is suggested. Anomalies in vibronic structures of the 4 $^1\Sigma^+$ and 5 $^1\Sigma^+$ states are understood by comparing with high-level *ab initio* calculations currently available. The avoided crossing energies are also experimentally estimated. These lead to irregularities in their vibronic structures. Our results can be complementary to those reported by Wang et al.[1] Wang et al. investigated the same energy region in a longer range of R through the transitions from the $a\ ^3\Sigma^+$ ($v"$=20 and 21) and $X\ ^1\Sigma^+$ ($v"$=89) and other levels. The combined results between this experimental result and photoassociation result will be useful for seeking efficient routes for formations and detections of ultracold KRb molecules to the ground state.

[1]D. Wang, E. E. Eyler, P. L. Gould, and W. C. Stwalley, J. Phys. B: At. Mol. Opt. Phys. **39**, S849 (2006).

Electromagnetically induced absorption with narrow spectral width in paraffin coated Rb vapor

H.J. Kim, H.S. Moon

Department of Physics, Pusan National University, Busan, Korea

The electromagnetically induced absorption (EIA), the opposite phenomenon of electromagnetically induced transparency (EIT), is the enhanced absorption due to the atomic coherence between the degenerated excited levels transferring spontaneously to the degenerated ground levels. The spectral width of the EIA spectrum is related to the atomic coherence between the ground states and the interaction time with atoms and laser. In the case of a pure atomic vapor cell, the atomic coherence between the ground states is limited by wall-collision and the interaction time is limited by laser beam size[1]. But the observation of EIA is difficult in an atomic vapor cell with a buffer gas, because EIA resonances are suppressed when the coherence of the excited state is destroyed by collisions[2].

We report the electromagnetically induced absorption (EIA) with narrow spectral width due to the wall-induced Ramsey effect in a paraffin coated Rb vapor cell[3]. We first observed the double-structure spectrum of the EIA in Hanle configuration of the $5S_{1/2}(F=2) \longrightarrow 5P_{3/2}(F'=3)$ transition of ^{87}Rb atoms. Figure 1 shows the EIA resonance in the Hanle configuration with the paraffin coated Rb vapor cell at room temperature, where the horizontal axis of the figure is the longitudinal magnetic field parallel to the laser's propagation generated by the solenoid coil. We can observe the interesting double structure EIA spectrum in the paraffin coated Rb vapor cell. The linewidth of the EIA spectrum was measured to be 0.55 mG ($2\pi\times$400 Hz) with the linearly polarized laser. Narrowing spectral width was explained by the wall-induced Ramsey effect preserving the atomic coherence between ground states while the atoms collided with the anti-relaxation coated wall of the Rb vapor cell.

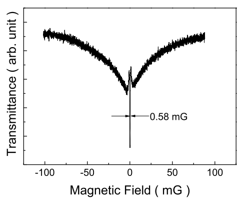


Figure 1: *Double structure EIA spectrum in the paraffin coated Rb vapor cell*

[1] F. Renzoni, C. Zimmermann, P. Verkerk, and E. Arimondo, J. Opt. B: Quantum Semiclass. Opt. 3, S7 (2001).

[2] H. Failache, P. Valente, G. Ban, V. Lorent, and A. Lezama, Phys. Rev. A 67, 043810 (2003).

[3] M. T. Graf, D. F. Kimball, S. M. Rochester, K. Kerner, C. Wong, D. Budker, E. B. Alexandrov, M. V. Balabas, and V. V. Yashchuk, Phys. Rev. A 72, 023401 (2005)

Magic polarization for a perturbation-free ground hyperfine spectroscopy in an optical trap.

Huidong Kim, D. Cho

Korea University, Seoul, Korea

A pair of ground hyperfine levels of an alkali-metal atom in an optical trap experience different ac Stark shifts due to the difference in detuning caused by the hyperfine splitting. This results in a shift of resonance frequency and inhomogeneous broadening of the hyperfine transition as well as dephasing of a superposition state in an optical trap. We propose a way to eliminate the differential ac Stark shift for a ground-state hyperfine transition in an optical trap by using a properly polarized trapping field. The ac Stark shift contribution from the vector polarizability has opposite sign for a pair of ground hyperfine levels with nonzero magnetic quantum numbers. It can be used to compensate the difference in the scalar polarizabilities due to the hyperfine splitting. The size of the vector term is determined by the polarization state of the trapping field, and by controlling the polarization tightly one can achieve a very narrow linewidth. The required tolerance in the polarization control depends on the ratio of the vector to scalar polarizabilities. The tolerance is largest for a lithium atom among the alkali-metal atoms because of its small fine structure. We are constructing a lithium apparatus for the magic polarization experiment and we will report the progress.

Spectroscopic analysis of the 1 $^1\Pi$, 2 $^3\Sigma^+$, and 1 $^3\Pi$ states of the ^{39}K^{85}Rb diatomic molecule using molecular beam and ultracold photoassociation experiments

J.T. Kim[1], Y. Lee[2], D. Wang[3], B. Kim[4], E. E. Eyler[5], P. L. Gould[5], W. C. Stwalley[5]

[1]*Department of Photonic Engineering, Chosun University, Gwangju, 501-759, Korea*
[2]*Department of Chemistry, Mokpo National University, Jeonnam 534-729, Korea*
[3]*JILA, National Institute of Standards and Technology and the University of Colorado, USA*
[4]*Department of Chemistry, KAIST, Daejeon 305-701, Korea*
[5]*Department of Physics, University of Connecticut, Storrs, CT 06269, USA*

We investigate the spectroscopic characterization of excited electronic states of the ^{39}K^{85}Rb diatomic molecule by combining spectroscopic lines from molecular beam (MB) experiments with those obtained using photoassociation (PA) of ultracold atoms. Spectra involving the 1 $^1\Pi$, 2 $^3\Sigma^+$, and 1 $^3\Pi$ states have been identified in this strongly perturbed region. This approach provides a powerful method to identify the vibrational levels perturbed globally by neighboring electronic states. This is because the two sets of spectra have differing selection rules corresponding to large internuclear distances (PA) and near the equilibrium distance of the ground electronic state (MB). Only the Ω=1 levels of the 2 $^3\Sigma^+$ state are observed in MB spectra, while both the Ω=1 and 0^- levels are observed in PA spectra. Proposed routes to transfer population from highly vibrationally excited levels of the X $^1\Sigma^+$ and a $^3\Sigma^+$ states formed by PA to the lowest vibrational levels of the X $^1\Sigma^+$ ground state are confirmed by comparing the intensities from these two types of spectra. These proposed routes provide new spectroscopic tools to explore the high density of rovibronic structure where the three excited states in our title mutually perturb each other. We hope to use this approach to unravel this structure and find optimal routes for formation of the lowest X $^1\Sigma^+$ state vibrational level of ultracold ^{39}K^{85}Rb.

Exponential increase of energy level density in atoms: Th and Th II

V.A. Dzuba, V.V. Flambaum,

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

We present analytical estimates and numerical calculations showing that the energy level density in open-shell atoms increases exponentially with increase of excitation energy. As an example, we use the relativistic Hartree-Fock and configuration interaction methods to calculate the density of states of Th and Th II. The result is used to estimate the effect of electrons on the nuclear transition which is considered for the use in a nuclear clock.

The results of the calculations for the total density of states are shown on Fig. 1 by points. It is also shown that the calculated data is fitted very well by simple exponential functions. We use two fitting formulae

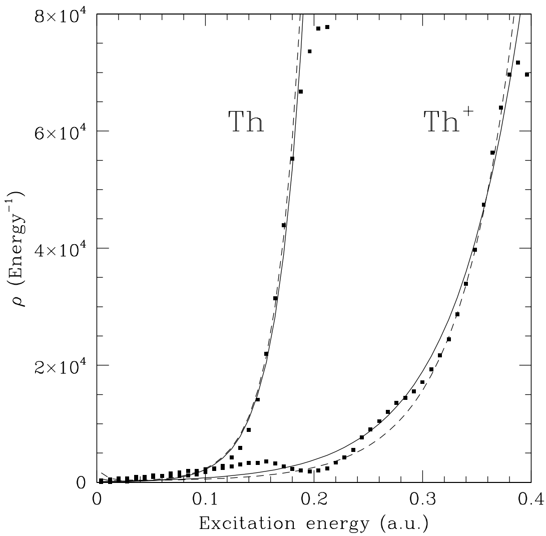
$$\rho(\epsilon) = \frac{A}{\epsilon_0}\exp(\epsilon/\epsilon_0)$$

(solid line on Fig. 1) and

$$\rho(\epsilon) = \frac{A}{\epsilon}\exp(\epsilon/\epsilon_0),$$

(dashed line on Fig. 1) where A and ϵ_0 are fitting parameters.

The density in Th I is higher since the number of electrons in the open shell is larger, $n = 4$, and the interval between the single-particle levels ω is smaller.



Progress Towards an Improved Comparison of Electron and Positron Magnetic Moments and Test of Lepton CPT Violation

S. Fogwell Hoogerheide, J.C. Dorr, G. Gabrielse

Harvard University, Cambridge, MA, USA

The most precise determination of the electron magnetic moment has been made using a one-electon quantum cyclotron in a cylindrical Penning trap. The result, g/2 = 1.001 159 652 180 73 (28) [0.28 ppt][1], is 15 times more accurate than the long standing measurement from the University of Washington in 1987[2]. An entirely new apparatus, specifically designed for maximum stability, will allow for an improved measurement of the electron magnetic moment. A positron source has also been incorporated into the new apparatus, enabling a measurement of the positron g-value at the same or better precision than the most recent electron measurement. Thus, our new apparatus should yield a measurement of the positron magnetic moment that would be a factor of at least 15 times more accurate than the previous positron measurement, also from 1987[2]. As the current best test of CPT violation in a lepton system comes from the comparison of these previous electron and positron measurements, our new measurement will yield a new best limit on lepton CPT violation.

A new Penning trap has been completed and incorporated into our new cryostat. This new trap has a mode structure that is slightly modified from previous traps to enable some new techniques to improve our precision. Preliminary measurements with electrons are underway to optimize the detection circuit and characterize the mode structure of the new trap. The positron loading system is in the last stages of assembly and will soon be incorporated into the setup. Once we are able to load positrons, the first step will be demonstrating a one-positron self-excited oscillator. The next step will be performing single quantum transitions of the cyclotron and spin degrees of freedom of a single positron, leading to a new, fully quantum measurement of the positron magnetic moment.

[1]D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. 100, 120801 (2008)

[2]R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, Phys. Rev. Lett. 59, 26 (1987)

Towards an Improved Limit on the Electron Electric Dipole Moment in Thorium Monoxide

P.W. Hess[1], B. Spaun[1], W.C. Campbell[2], Y.V. Gurevich[1], N.R. Hutzler[1], E. Kirilov[3], M. Parsons[1], E. Petrik[1], A. Speck[4], A.C. Vutha[3], D. DeMille[3], J.M. Doyle[1], G. Gabrielse[1]

[1] *Harvard University, Cambridge, MA, USA*
[2] *University of Maryland, College Park, MD, USA*
[3] *Yale University, New Haven, CT, USA*
[4] *Rowland Institute at Harvard, Cambridge, MA, USA*

Many theories of physics beyond the standard model predict new sources of T-violation, producing an electron electric dipole moment (eEDM) just below the current experimental limit of 1.6×10^{-27} e·cm[1]. Our experiment proposes to search for the signs of an eEDM in the metastable H state of Thorium Monoxide (ThO). A cold molecular beam experiment with ThO provides several advantages over other eEDM measurements. These include the large effective electric field of polarized ThO, the long lifetime and magnetic field insensitivity of the metastable H state, and the powerful systematic error canceling provided by the Ω-doublet structure of the H state. These properties significantly reduce sources of statistical and systematic error, allowing for a projected sensitivity at the level of 10^{-29} e·cm in a first generation experiment and up to 10^{-32} e·cm with future improvements.

Our measurement will utilize Ramsey interferometry on a cold molecular beam of ThO. Significant progress has been made in characterizing and optimizing our ablation based buffer gas cooled ThO molecular beam source. First steps are being taken in testing a "molecular oven" based beam source, which could provide many improvements over the ablation based source[2].

We report on advances in characterizing the spectroscopic properties of the ThO molecule. Key transitions necessary for H state preparation and detection have been observed for the the first time, and the saturation parameters for these transitions have been measured. The lifetime of the state used to probe the molecular beam dynamics has been measured, allowing a more accurate calculation of the flux of usable molecules in the beam. Progress is also underway to measure the g-factor of the H state itself.

---

[1] B.C. Regan, E.D. Commins, C.J. Schmidt, D. DeMille, "New Limit on the Electron Electric Dipole Moment", PRL 88, 171805 (2002)

[2] A.C. Vutha, W.C. Campbell, Y.V. Gurevich, N.R. Hutzler, M. Parsons, D. Patterson, E. Petrik, B. Spaun, J.M. Doyle, G. Gabrielse, D. DeMille, "Search for the electric dipole moment of the electron with thorium monoxide", Journal of Phys. B 43, 074007 (2010)

Radium fluoride as a prospective molecular candidate for measurement of nuclear spin-dependent parity violation and for direct laser cooling

T.A. Isaev, R. Berger,

Clemens-Schöpf Institute, TU Darmstadt, Petersenstr. 22, 64287 Darmstadt, Germany

Compared to nuclear spin-independent parity violation (NSIPV) effects, the nuclear spin-dependent counterpart (NSDPV) does not grow so fast with the nuclear charge in atomic systems (Z^3 vs. Z^2), which poses a major challenge for high accuracy measurements of NSDPV. In diatomic molecules, however, only the NSDPV term can contribute in lowest order to the conventional parity conserving effective spin-rotational Hamiltonian[1]. The strength of this contribution is characterised by the electronic structure dependent parameter W_a.

We computed W_a for the electronic ground state of radium fluoride (RaF) and found it to belong to the largest absolute values predicted so far. These calculations were performed with the complex generalised Hartree-Fock method within a two-component (quasi-relativistic) zeroth-order regular approximation framework. Four-component (relativistic) coupled-cluster calculations with singles and doubles (CCSD) provided the potential energy curves for the six lowest-lying electronic states of RaF. The resulting Franck-Condon (FC) matrix between vibrational states of the electronic ground and first excited state was found to be highly diagonal, which renders the molecule especially suitable for direct laser cooling[2].

[1] M. Kozlov and L. Labzowsky, *J. Phys. B*,**28**,1995

[2] M.D. DiRosa, *Eur. Phys. J. D*, **31**, 2004; B.K. Stuhl *et al*, *Phys. Rev. Lett.*, **101**, 2008

State detection of auto-ionized HfF for an electron EDM search

H. Loh, R. P. Stutz, M. Grau, T. Yahn, E. A. Cornell

JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, CO 80309-0440, USA

A sample of trapped molecular ions offers unique possibilities to search for a permanent electron electric dipole moment (eEDM). Specifically, the $^3\Delta_1$ state of HfF^+ has been proposed as a candidate for the eEDM search. By laser ablation of a Hf target in the presence of Ar + $1\%SF_6$, we create neutral HfF molecules and cool them rotationally via supersonic expansion. The neutral molecules are optically excited with two photons to an autoionizing state, from which they decay to form ions. We report the observation of laser-induced fluorescence of these ions on the $^1\Sigma_0 \rightarrow ^3\Pi_1$ transition.

Injection Locking of a Trapped Ion Phonon Laser - YoctoNewton Force Detection

S. Knünz[1], M. Herrmann[1], V. Batteiger[1], G. Saathoff[1], K. Vahala[2], T.W. Hänsch[1], T. Udem[1]

[1]*Max–Planck–Institut für Quantenoptik, 85748 Garching, Germany*
[2]*California Institute of Technology, Pasadena, California 91125, USA*

If a single trapped ion is addressed by both a red-detuned cooling laser and a blue-detuned pump laser it can exhibit stable oscillatory motion with a well defined threshold. We have shown that this oscillation is the result of stimulated emission of center-of-mass phonons, thus this oscillator constitutes a mechanical analogue of an optical laser[1]. Now we report on injection locking of this oscillator to an external rf signal. Using phase sensitive stroboscopic imaging and a spatially selective Fourier transform technique to generate motional spectra (Fig. 1) we find excellent agreement with injection locking theory in- and outside the locking range[2]. Since we have attained injection locking with forces as small as 15 yN (yocto= 10^{-24}), this system appears to be promising for ultra-sensitive force measurements, e.g. the detection of nuclear spin flips of single ions or molecules.

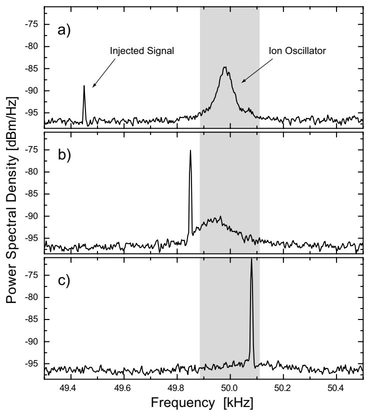


Figure 1: *Measured motional frequency spectra of a single ion in- and outside the locking range (shaded area). In a) and b) both the ion oscillation and the injected frequency are visible. The spectral width of the ion oscillation is given by its regenerative linewidth, the width of the injected signal is limited by the instrumental resolution. In b) the injected signal was set closer to the unperturbed frequency of the ion. As expected, the injected signal is amplified in favor of the free-running oscillation. Further, the free-running frequency is pulled towards the injected signal and its width has increased. Within the locking range (c), only the amplified injected signal prevails.*

[1]K. Vahala et al., Nature Physics 5, 682 (2009)
[2]S. Knünz et al., submitted to Phys. Rev. Lett.

Micro-Structured Ion Traps for Optical Clocks

T.E. Mehlstäubler[1,2], K. Pyka[1], J. Keller[1] N. Herschbach[1]

[1]*QUEST at PTB*
[2]*Department of Time and Frequency, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

In the cluster of excellence QUEST (center for Quantum Engineering and Space-Time research) atomic clocks are developed for a new kind of quantum sensors and tests of fundamental theories, like Einstein's General Relativity or modern unifying theories, that predict a temporal variation of fundamental constants. Our work is targeted on the development of new optical frequency standards with the potential of a short term stability of $y < 10^{-15}$ in 1s and long term stability of 10^{-18}, which will open up new applications in geodesy and navigation.

Today's best standards are defined by single-ion clocks and neutral atom optical lattice clocks, which have demonstrated the potential for ultra-high short term stability and ultra-high accuracy, respectively. Our group dedicates its work to the development of new trap geometries for the trapping, manipulation and spectroscopy of many ions to combine the advantages of both and overcome the problems of the current technologies.

We have set up a new experiment to trap ions in micro-fabricated trap structures. $^{172}Yb^{+}$-ions serve to test and characterize the new trap geometries as well as to sympathetically cool $^{115}In^{+}$-ions, which will be used for the spectroscopy. As the clock transition in indium ions is free of quadrupole shift, chains of ions can be stored in linear ion trap configurations without ion number and position dependent frequency shifts. First tests are carried out in an ion chip-trap made out of Rogers4350 printed circuit board, a high-precision ceramic chip trap is built in parallel. We present the status of our experiment together with FEM-simulations of the new trap designs.

Chacterisation of a Phase Fresnel Lens for Imaging Trapped Ions

B.G. Norton[1], E.W. Streed[1], A. Jechow[1], T.J. Weinhold[2], D. Kielpinski[1],

[1]*Centre for Quantum Dynamics, Griffith University, Brisbane 4111, Queensland, Australia*
[2]*QT Lab, University of Queensland, Brisbane 4072, Queensland, Australia*

Quantum computers use the unique properties of quantum physics to provide solutions to challenging problems in classical computer science. One leading technology to realize quantum computers is ion trapping due to its scalable architecture, high fidelity readout, long coherence times and controllable interactions. Readout of an ion's state is performed by collecting and detecting scattered photons.

An imaging lens with a high numerical aperture is advantageous because it collects light from a large solid angle. This increases the probability of collecting an emitted photon, resulting in a faster quantum state measurement with greater signal to noise. Phase Fresnel lenses (PFLs) combine high numerical apertures with long working distances. These lenses can be easily arrayed for large-scale quantum computing due to the micro fabrication process.

We characterised a PFL that was fabricated by electron-beam lithography on a fused silica substrate. This PFL had a numerical aperture of 0.64 and a working distance of 3mm. Profiling of the PFL was conducted using a knife edge beam profiler to accurately measure sub-micron beam waists[1]. We obtained a beam waist radius of 350 ± 15 nm and a beam quality M^2 of 1.08 ± 0.05[2].

Unlike a conventional lens, a PFL's diffraction efficiency depends on the spatial location of the incoming light on the lens surface. We measured the spatial variation of the diffraction efficiency for both S and P polarisations. Grating periods less than 1.5 μm exhibited vector diffraction. In this regime the diffraction efficiency has a strong polarisation dependence resulting in a higher diffraction efficiency for P polarised light. For grating periods larger then 1.5 μm, the light undergoes scalar diffraction which is polarisation insensitive. An overall diffraction efficiency into the focusing mode of $30\pm1\%$ was obtained[2].

After profiling, the PFL was integrated with an ion trap allowing cooled Yb^+ ions to be imaged[3]. A detailed analysis of the profiling data will be presented and a comparison between profiling and imaging will be made.

[1]J. J. Chapman, B. G. Norton, E. W. Streed, and D. Kielpinski (2008) Rev. Sci. Instrum. 79, 095106
[2]E. W. Streed, B. G. Norton, J. J. Chapman and D. Kielpinski (2009) Quantum Information and Computation. 9 pp0203-0214
[3]E.W. Streed, B.G. Norton, A. Jechow, T.J. Weinhold, D. Kielpinski (2010) Submitted to ICAP

Observation of a ring Coulomb crystal of Ca^+ ions in a linear hexapole rf ion trap

K. Okada[1], T. Suganuma[1], N. Kimura[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*

Linear multipole rf ion traps generate very flat pseudopotentials in the radial direction that result in producing new types of Coulomb crystals by applying laser cooling to trapped ions. Our previous simulations show that crystallized ions form cylinder-like and ring structures in a linear octupole and multipole rf ion traps [1]. In the experiment cylinder-like crystals of Ca^+ were successfully observed for large number of Ca^+ ions using the cryogenic octupole trap [2]. However, the ring Coulomb crystal with a small number of ions was not confirmed.

Here we report experimental observation of planar ring Coulomb crystals consisting of a small number of ions in a linear hexapole rf ion trap. Such planar crystals open up novel applications for quantum information processing and quantum computing [3]. The ring structure was confirmed by direct observation from the axial direction in the linear trap. Fluorescence images are shown in Fig. 1 with the same scale. The cooling lasers were irradiated in the radial direction. Figure 1(b) shows an observed ring Coulomb crystal with a diameter of about 50 μm. We presume the crystal to be composed of $\sim$10 ions from the single ion image of Fig. 1(c). Although the hexapole fields provide stronger confinement force to trapped ions compared to the octupole fields, a Coulomb crystal is still influenced by the patch effect of electric charges and is arranged as a deformed (asymmetric) shape. Moreover the radiation pressure force pushes the crystal to the radial direction (to the left of the image) and possibly deforms a ring structure. Therefore we have to apply correction DC voltages to the hexapole rods to shape the ring structure. In the presentation, we will report the experimental setup and the production process of the ring Coulomb crystals in detail. For comparison the results of molecular dynamics simulations will also be presented.

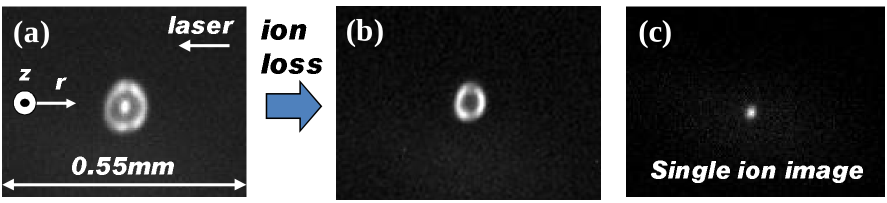


Figure 1: *Fig.1 Observed images of a ring-type Coulomb crystal with a central ion (a), a ring crystal (b), and a single ion (c).*

[1]K. Okada *et al.*, Phys. Rev. A 75, 033409 (2007)
[2]K. Okada *et al.*, Phys. Rev. A.80, 043405 (2009)
[3]J. I. Cirac and P. Zoller Nature **404**, 579 (2000)