Single Ion Imaging with a Microfabricated Optic

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Trapped ions are a leading technology for implemented quantum computing. Small scale demonstrations have already been realised and a roadmap exists for scaling to larger processes[1] through an architecture of multiple parallel processing regions implemented on a microfabricated trap. A limiting factor in the realisation of large scale quantum computation is the development of a scalable method for efficiently coupling light out of the trapped ions. Arrays of micro-fabricated phase Fresnel lenses (PFLs) are a promising solution [2] to this problem as they are easily scalable and have high numerical aperture for capturing a large fraction an ion's solid angle. Figure 1a. indicates how a PFL array could be combined with a microfabricated trapped ion Quantum CCD processor architecture for parallel readout. The diffraction limited performance[2] of PFLs with large numerical apertures also makes them suitable for obtaining large coherent coupling between an individual ion and a single optical mode, crucial to realising large scale quantum networks through remote entangling protocols.

To demonstrate the feasibility of this approach we have integrated together an RF needle trap with an in vacuum, large aperture PFL (Fig 1b) which captures light from 12% of the total solid angle (NA=0.64). Single $^{174}Yb^{+}$ ions were loaded into the RF quadrupole potential formed between the needles through isotope selective photoionisation. The emitted ion fluoresce from laser cooling was subsequently imaged with the PFL. We have observed a depth of field of 30μm and a field of view in excess of 100μm for ions with a spatial width ($1/e^2$) of 4.4μm, limited by the ions motion. Correcting for a reduction in the ions maximum brightness due to this motion we observed an overall collection efficiency of $4.2 \pm 1.5\%$ and a signal to noise ratio of 23 ± 4. This readout performance is sufficient for large scale quantum processing[2].

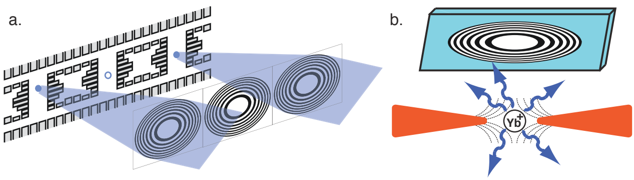

Figure 1: *a. Phase fresnel lens array for large scale quantum computing*[1]. *b. Experimental apparatus configuration.*

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Ultra-Sensitive Magnetometry using Atoms in Fibres

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One real-world application of atomic vapour spectroscopy is the precision measurement of magnetic fields. As one example, SERF atomic magnetometers have been realised with sensitivities of 0.5 fT $Hz^{-1/2}$, surpassing that of SQUID-based magnetometers[1]. These ultra-sensitive magnetometers are capable of measuring biological magnetism from the heart (magnetocardiography) and brain (magnetoencephalography), however, they can only be operated at very low magnetic fields. For high field applications, we aim to build an all-fibre atomic magnetometer using the phenomenon of coherent population trapping.

Coherent population trapping occurs when atoms (of Rubidium, for example) are exposed to a multimode optical field containing two frequency components separated by the ground state hyperfine splitting. When this happens, the atoms can be optically pumped into a “dark state”: a coherent superposition of the two ground states which doesn’t interact with the optical field. The narrow “dark state” resonance has applications in miniaturised atomic frequency standards[2], quantum memory[3], and magnetometry[4]. The two most common ways of generating the two-component optical field are by modulating a laser to generate sidebands, or by phase-locking two lasers. Preliminary measurements have been made by modulating a diode laser and performing spectroscopy on a magnetically shielded Rubidium-85 vapour cell. We have succeeded in measuring the CPT resonance and have used this to see a magnetic field.

In the future, we intend to use a specially fabricated self-modulating diode laser incorporating a resonant tunnelling diode (RTD): the fastest known electronic devices (demonstrated operation at 831 GHz[5]). The RTD has intrinsic electronic gain and can generate self-sustaining modulation, eliminating the need for a microwave oscillator. In addition, we aim to use Rubidium vapour loaded in a hollow-core photonic crystal fibre to replace the glass vapour cell. This approach has the advantage of combining the cell and laser in a self-contained all-fibre system that avoids any magnetic material near the compact and robust sensor.

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Precision measurements of the Casimir force between metallic and semiconducting plates

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Casimir effect describes short-range quantum forces between a pair of macroscopic objects. The Casimir force is among the dominant forces affecting MEMS and NEMS, causing stiction and dissipation, and the possibility to control this force can have enormous technological benefits. Measurements of the short-range attractive force between a pair of plates separated by 0.7 μm to 100 μm have been performed using a torsion balance. The force between crystalline germanium plates is found to contain contributions from both the Casimir force and a residual electrostatic force, generated by surface patch potentials. We have developed a model, taking into account long-range variations in the contact potential across the plate surfaces, which reproduces our experimental observations. Improved-precision measurements of the attractive force between plates covered with a carefully prepared gold film show that the patch-potential electrostatic force is essentially absent, and the Casimir force can be extracted with improved accuracy.

Techniques to reduce the acceleration sensitivity of cavity stabilized lasers*

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We present techniques to reduce the acceleration sensitivity of laser local oscillators (LLO). LLOs with a high fractional frequency stability ($\sim 1 \times 10^{-15}$ or better) play a crucial role in a range of scientific investigations including: optical atomic clocks, gravitational wave detectors, and searches for time-variation of fundamental constants. State-of-the-art LLOs are currently based on lasers that are tightly locked to well isolated Fabry-Perot (FP) cavities with the Pound-Drever-Hall locking technique. All FP cavity designs are sensitive to accelerations and it remains a challenge to reach shot noise and thermal noise limited performance.

In response to this problem, we have developed two approaches to reduce the acceleration sensitivity of FP cavities. The first uses a spherically symmetric cavity spacer to reduce the intrinsic acceleration sensitivity of the cavity length to 10^{-10} dL/L/g. The spherical spacer is held rigidly at a 'magic angle' that suppresses changes in the cavity length due to squeezing of the mounting structure. The rigid mounting structure makes the cavity robust against misalignment in situations where it is bumped or moved. The second approach uses measurements of the accelerations experienced by an FP cavity to cancel the resulting frequency fluctuations in real-time. Measurements from six accelerometers positioned around the cavity are input into a field programmable gate array (FPGA) that implements a Wiener filtering algorithm to predict the frequency fluctuations. The FPGA also controls the frequency of an acousto-optic modulator positioned before the cavity, which cancels the fluctuations in real-time.

*Supported by ONR

Ultrahigh-fidelity quantum gates using smooth composite pulses

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Excitation by composite pulses is routinely used in nuclear-magnetic-resonance experiments, in order to achieve excitation profiles with prescribed shapes[1,2]. The method consists of applying several consecutive pulses with appropriate relative phases. In such way one can achieve a robust analog of the traditional resonance pulses. This technique is, however, mainly developed for pulses with rectangular temporal shape.

In this work we show that composite pulses with smooth temporal shape can be used to obtain analogues of the π-pulses with arbitrarily flat excitation profile. The transition probability can be made robust against variations in the pulse area and/or the detuning. As the number of pulses increases, the excitation profile becomes increasingly insensitive (flat) to small deviations. In order to achieve this, we use the well-known analytic solution of the Rosen-Zener model[3], which assumes a hyperbolic-secant pulse shape and a constant detuning:

$$\Omega(t) = \Omega_0 \text{sech}(t/T), \quad \Delta(t) = \Delta_0, \tag{1}$$

where $\Omega(t)$ is the Rabi frequency, and Ω_0, Δ_0 and T are constant parameters. We calculate the total propagator by multiplying the phased propagators for each pulse. Then we take the Taylor expansion of the full propagator and nullify the first few terms in the respective series (vs. the pulse area deviation or vs. the detuning). The more composite pulses we use, the more terms we are able to nullify, and the more flat the profile will be.

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High Accuracy Spectroscopy of Alkali Metals for the Determination of the Boltzmann Constant

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The recently developed technique of Doppler-broadened absorption spectroscopy has been shown to be a viable new method for highly accurate determinations of the Boltzmann constant (k_B). In 2009, Djerroud *et. al.*[1] reported a determination with a relative uncertainty of 3.8×10^{-5}, using NH_3 at the freezing point of water. A similar experiment using CO_2 transitions[2] has derived a value of k_B with a relative uncertainty of 1.6×10^{-4}.

We will report on the progress of an alkali-atom Doppler-spectroscopy effort underway at the University of Western Australia. Unlike the molecular experiments, strongly absorbing alkali metal gases allow us to use compact, low pressure reference cells which are amenable to high temperature uniformity while avoiding pressure-induced perturbations seen in higher pressure regimes. However, these advantages are traded-off against the larger homogeneous to inhomogeneous linewidth ratio ($\sim 1/100$), requiring the non-linear fitting process (used to extract k_B from the inhomogeneous component) be extremely robust. In addition, strong optical pumping effects and unresolved hyperfine structure in the D_2 lines of Rb and Cs complicate the spectrum by perturbing the Doppler-broadened lineshape, introducing a systematic error that is challenging to model.

Using Rb and Cs vapours, we have determined the Boltzmann constant with a relative uncertainty of 4.0×10^{-4}. We are currently limited by low signal-to-noise ratio (SNR), imposed by the requirement to operate at very low intensities to avoid both population and lineshape perturbations. To remove this restriction and allow us to use greater probe powers, thereby improving the SNR, we have developed a detailed model[3] with no fitting or phenomenological parameters that accounts for the ballistic motion of open three-level atoms through a probe beam with gaussian spatial profile. We will show that this model agrees with experiment at the few percent level over four orders-of-magnitude of probe power. The success of this theory will allow spectroscopists to depart from phenomenological models, and will allow us to improve our determination of the Boltzmann constant in future experiments, by providing a reliable way to extrapolate high SNR results to the zero-probe-power limit.

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Precision Measurement of the Decay Rates to the Ground State for the Helium n=2 Triplet Manifold

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This work represents the first complete measurement of the radiative decay rate to the ground state of the n=2 triplet states of helium i.e. the metastable $2\,^3S_1$ state and the $2\,^3P$ manifold. We employ laser cooling and trapping in an ultrahigh vacuum chamber to enable direct measurement of the trap loss rate for decay from the $2\,^3P_1$ state to the ground state. We then use this rate to calibrate the XUV emission decay to the ground state for all the remaining transitions. The $2\,^3P_1$ [1] and $2\,^3P_2$ [2] transition rates are measured for the first time, an upper bound is placed on the $2\,^3P_0$ decay rate, and the $2\,^3S_1$ metastable lifetime is determined for only the second time with a five-fold improvement in accuracy [3]. A summary of the ratio of our experimental values to the most recent theoretical determinations [4] is shown in figure 1.

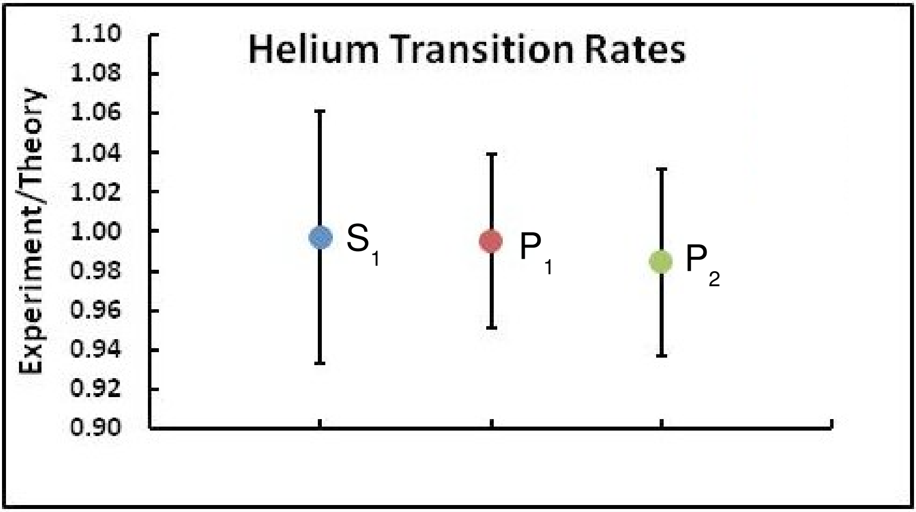

Figure 1: *Ratio of present experimental results to the most current QED theory* .

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Investigation of Highly Sensitive Atomic Magnetometer

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Highly sensitive magnetometers capable of measuring magnetic fields below 1 pT are important for many applications such as geophysical surveying, space science, medical diagnoses etc. For decades, superconducting quantum interference devices (SQUIDs) have been unrivalled as ultrahigh-sensitivity magnetic field detectors, with a sensitivity of 1 $\mathrm{fT/Hz^{1/2}}$.

The atom magnetometer is based on the measurement of Larmor spin precession of optically pumped atoms. It has reached and even surpassed[1] the sensitivity of SQUIDs. It can also be very compact which is important in magnetic imaging applications. Due to higher sensitivity and spatial resolution, atomic magnetometers would enable new applications.

We report a simple and highly sensitive all-optical atomic magnetometer that uses the advanced technique of single laser beam detection based on the interaction between laser beam and rubidium atoms in magnetic field[2]. This interaction is dependent on the magnetic field surrounding the Rb atom cell, therefore the magnetic field information can be obtained by measuring the changes of the laser power transmitted through the Rb atom cell. A sensitivity of $0.5\mathrm{pT/Hz^{1/2}}$ has been achieved by analyzing the magnetic noise spectrum, which exceeds that of most traditional magnetometers. This kind of atomic magnetometer is very compact, has low-power consumption, and has a high theoretical sensitivity limit, which make it suitable for many applications.

We also analyzed some important factors that may affect the sensitivity of the magnetometer, such as the temperature of the Rb cell, laser intensity, detuning, polarization, diameter, and the ways to improve the sensitivity of the atomic magnetometer. It is shown that higher sensitivity can be obtained by using laser with larger diameter, higher polarization, smaller detuning, choosing an optimum temperature and laser intensity.

This work was supported by the National Natural Science Foundation of China (60925022 & 10804097) and the Research Fund for the Doctoral Program of Higher Education of china (20090101120009).

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Cold atom gravimeter for onboard applications

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Atom interferometry is now proven to be a very efficient technique to achieve highly sensitive and absolute inertial sensors. As a matter of fact accelerometers such as gyroscopes [1] or gravimeters [2] based on this technique by using cold atoms have already been developped. However state of the art laser cooling techniques are still too sensitive to environmental disturbances to ensure onboard applications with such instruments.
We are presently developping a Rb^{85} cold atom gravimeter based on a compact and reliable laser system operational in onboard conditions. The optical system relies on the frequency doubling of a telecom fiber bench at 1560 nm [3]. The starting point of the gravimeter is a vapour loaded MOT of $\approx 10^8$ atoms. The atoms are then released and during the fall a sequence of three Raman pulses forms a Mach-Zehnder type interferometer. The interferometer's phase, which depends on the gravity acceleration, is finally read by means of a fluoresence detection measuring the population of the two atomic states involved in the raman transitions.
Besides last results we obtain on gravity acceleration measure, we will present the details of the experiment setup and particularly the optical part which partly garantees the onboard character of the gravimeter. This laser setup has already been tested successfully under micro ($\approx$ 0g) and hyper ($\approx$ 2g) gravity inside the CNES ZERO-G Airbus plane in the frame of the ICE (*Interférométrie Cohérente pour l'Espace*) project [4].
We are also implementing a new technique for measuring the gravitational acceleration relying on the use of light pulse atomic interferometry with atoms performing Bloch oscillations in a vertical optical lattice [5]. This should significatively reduce the falling distance of the atoms, which set the height of cold atom gravimeters, without decreasing the sensitivity of the instrument.

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A Quantum Degenerate Source for Atom Interferometry

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We describe the creation of a quantum degenerate gas of Rb atoms in a single beam optical dipole trap at a wavelength of 1960 nm formed by a Thulium-doped fiber laser with 50 W output power. First, we study the loading of this dipole trap and find initial temperatures of the atomic cloud in the dipole trap as low as 2 μK, one order of magnitude below values achieved so far by means of simple polarization gradient cooling. We attribute these very low temperatures to a very favorable combination of the near resonant cooling light and the very far-off-resonant dipole trap laser field. The atomic source for loading the dipole trap consists of a two-stage design, where a three dimensional magneto-optical trap (3D MOT) is loaded by a 2D MOT. With this setup, we reach a very quick loading (less than 1 second) with high initial atom numbers and high phase space densities in the dipole trap.

Forced evaporative cooling is then performed by continuously reducing the laser power of the dipole trap, thus allowing the hottest atoms to escape the trap. However, this power reduction also leads to a decrease of the already weak confinement of the atoms along the axial direction of the trap and thus an eventually vanishing efficiency of the forced evaporation. We describe the development of a new trap configuration to counteract this reduction of the axial confinement. This new trap potential consists of the sum of the single beam dipole trap and the weak magnetic quadrupole field of the 3D MOT. The efficiency of evaporation could be increased significantly in this *weak hybrid trap* as compared to the single beam dipole trap and therefore enabled the first creation of a Bose-Einstein condensate of 10^4 Rb atoms in an optical dipole trap of this wavelength.

This work is motivated by the ultra-low temperatures feasible in BEC, thus possibly improving the accuracy of matter wave interferometers for precision measurements, such as e.g. the quantum test of the equivalence principle. Optical dipole traps make a fast production of BEC possible allowing for a high repetition rate in an interferometer. Additionally, dipole traps are able to trap all m_F-substates, especially $m_F = 0$, being insensitive to magnetic fields in first order.

Demonstration of Rydberg blockade between atoms in an optical lattice

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Due to the weaker interactions between ground state neutral atoms, it is very difficult to realize entanglement between neutral atoms. Atoms in highly excited Rydberg states have large transition dipole moment that causes the strong dipole-dipole interaction between atoms. Because of this strong dipole-dipole interaction, when several atoms are sufficiently close together the presence of a single excited atom can cause a shift in the energy of all other atoms which is large enough to prevent resonant excitation of more than one atom in a sample. This so-called ”Rydberg dipole blockade” has been demonstrated with two atoms separated by more than 1 micron [1] [2]. This provides a good tool to realize quantum information processing such as quantum gates and entanglement protocols. The basic necessity in order to realize the dipole blockade effect is the excitation of atoms from the ground state to a Rydberg state. Very recently, several groups have realized this Rabi oscillation[2] [3] [4].

Our group is interested in atom Rydberg interactions in the far-off-resonance optical dipole trap. Recently, we have prepared a single atom in the dipole trap and then demonstrate its coherent excitation to a Rydberg state. We have realized Rabi oscillation between ground and Rydberg states (n=43) with a single and two cold ^{87}Rb atoms in a small dipole trap[5]. Comparing Rabi oscillations of single atom and two atoms for n=43D and n=75D excited state, we preliminarily got the Rydberg blockade for highly excited atoms in a dipole trap. This is required step for future demonstrations of the entanglement, 2-qubit quantum gates and so on. Now we can observe several separated atoms independently with a very strong standing wave potential; next we will fix the distance between atoms and get Rydberg blockade visually by the image from the camera.

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Extending Coherence of Nitrogen-Vacancy in Diamond

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Nitrogen-Vacancy (NV) colour centres in diamond are gaining popularity as solid state qubits due to their exceptional coherence times at room temperature and convenient optical readout. Centers deep within ultrapure diamond have coherence times $> 1\text{ms}$[1] allowing coherent coupling over large distances[2]. However, the challenge remains to create NV on demand and in specialised devices whilst maintaining these advantageous properties. For example, long coherence times enable $0.5\ \mu\text{T Hz}^{-1/2}$ sensitivity[3] for magnetometry at nanometer scale, yet incorporation of NV into useable sensors and photonic devices inevitably leads to a reduction of coherence. Scalable architectures for quantum computing also require precise positioning of qubits. We investigate novel methods for extending coherence times of implanted centers in bulk crystal and nanodiamonds. Uhrig pulse sequences are used to optimally decouple NV from the environment and the local spin bath is modified in order to increase coherence times. The consequences for quantum information and magnetometry are discussed and recent experimental progress presented.

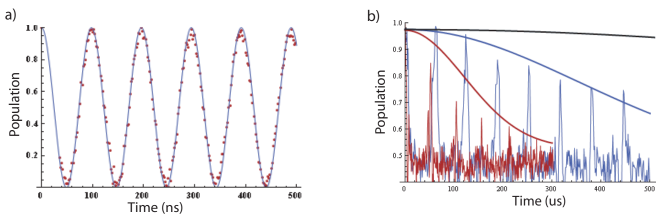

Figure 1: ***a)*** *Rabi oscillations of a single implanted NV center in ultrapure diamond.* ***b)*** *NV decoherence profiles from Uhrig pulse sequences.*

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Quantum interference of photons emitted by two remotely trapped atoms

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Entanglement between atomic quantum memories at remote locations is a key resource for future applications in quantum communication. Here we present our recent progress on establishing entanglement between two single Rb-87 atoms over a large distance. For this purpose we have set up two independently operating atomic traps situated in two neighboring laboratories (separated by 20 meter). On each side we capture a single neutral Rb-87 atom in an optical dipole trap and generate a spin-entangled state[1] between the atom and a photon. The emitted photons are collected with high-NA objectives into single-mode optical fibers and guided to a non-polarizing 50-50 fiber beam-splitter where they interfere.

After interference, the two photons leaving the output ports of the beam-splitter are detected by avalanche photodetectors. We observe bunching of indistinguishable photons, i.e. photons of the same polarization go preferentially into the same output port. First measurements show a bunching ratio of 1:3 with respect to orthogonally polarized photons which do not interfere. This bunching allows to perform a Bell-state measurement on the photons. By analyzing the polarization we are able to detect two out of four Bell-states (heralded by coincident detection of two photons in particular combinations of the four detectors), thereby projecting the atoms into an entangled state.

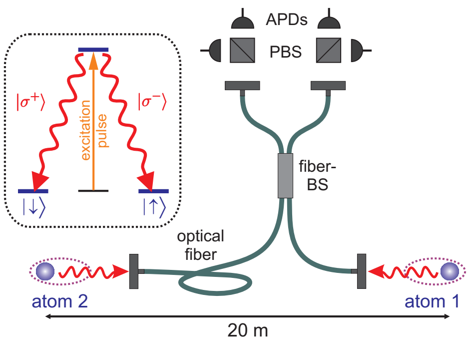

Figure 1: *Two single atom traps at a distance of 20 m are connected via optical fibers. The emitted single photons interfere on a 50-50 beamsplitter and are detected by single photon counting avalanche photodetectors (APDs). The inset shows the scheme for generation of single photons whose polarization is entangled with the atomic spin.*

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EIT in warm atomic vapors: beyond the Λ scheme approximation

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The quantum memories that are developed at Laboratoire Kastler Brossel are based on Electromagnetically Induced Transparency (EIT) in atomic ensembles [1]. The coherent interface between the input signal light and the matter is achieved by dynamically controlling a strong resonant control field. As the signal field propagates through the atomic medium, the group velocity is adiabatically reduced to zero, the quantum state being converted from a purely photonic state to a matter-like collective spin coherence. When the control field is reactivated, after a user-defined delay, the collective spin is coherently converted back into a photonic mode. Using this technique, our group has recently demonstrated the storage and retrieval of small coherent states, in a warm vapor of cesium atoms. Simultaneous storage of non commuting quadratures has been achieved with a retrieving excess noise lower than 1%, making it compatible with quantum operation [2].

Later study consisted in modeling in detail the influence of the hyperfine structure of the upper level of the D2 transition of cesium used in the experiment. Due to this structure, the EIT behavior is different from what it is in a simple Lambda system (two ground states and one excited state), and is very detrimental in warm vapors configuration.

While nonmoving atoms behave as perfectly transparent in the EIT conditions, some non zero velocity class atoms can induce extra absorbtion. Atoms that perceive a sufficient Doppler shift are involved in an off-resonant Raman process which induces absorption of light. Nevertheless, in a three levels atoms, transparency should be preserved at perfect two photon resonance for the control and signal fields. Indeed, the Raman transitions occur for small but non zero two photon detuning for the two fields. Thus, the effect of transparency is kept for all velocity classes at two photon resonance. In D2 line, due to the presence of several excited states (hyperfine structure), this Raman transition is frequency shifted. It can occur at two photon resonance for some velocity classes, which destroys the expected transparency.

To improve the EIT in vapors, we proposed an effective cooling mechanism through optical pumping. The aim was to burn a hole in the velocity distribution by adding pumping field judiciously detuned, such as to remove selectively the detrimental absorbing atoms. The predicted effect has been experimentally demonstrated in our lab, and significative enhancement of the EIT transparency has been observed.

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Deterministic resolution single ion source

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Within the next 5 years the increasing miniaturization of semiconductor devices might lead to dopant counts of less than one hundred in the channel regions of field effect transistors[1]. Conventional dopant techniques would then lead to high statistical fluctuations of dopants causing device parameters to vary at an unacceptable level. Ultimately, at the single atom limit, quantum devices like future quantum processors and future nano solid state devices call for new deterministic production techniques with nanometer. Based on a segmented ion trap with mK laser cooled ions we have realized a novel deterministic single ion source which can operate with a huge range of sympathetically cooled ion species, isotopes or ionic molecules (Fig. 1 left). We have deterministically extracted a predetermined number of ions on demand (Fig. 1 right) and have measured a longitudinal velocity uncertainty of 6.3m/s and a spatial beam divergence of 600 μrad [2]. We show in numerical simulations that if the ions are cooled to the motional ground state (Heisenberg limit) nanometer spatial resolution can be achieved with optimized ion optics [3]. First experimental results of the imaging systems are presented [4].

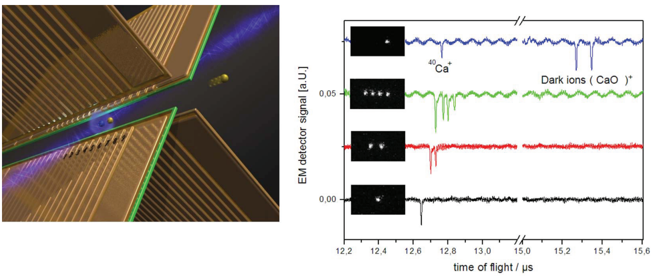

Figure 1: *Left: A segmented linear Paul trap as a deterministic single ion source. Right: Fluorescence images of single ion and of ion crystals and time-of-flight traces.*

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Entanglement detection from interference fringes in atom-photon systems

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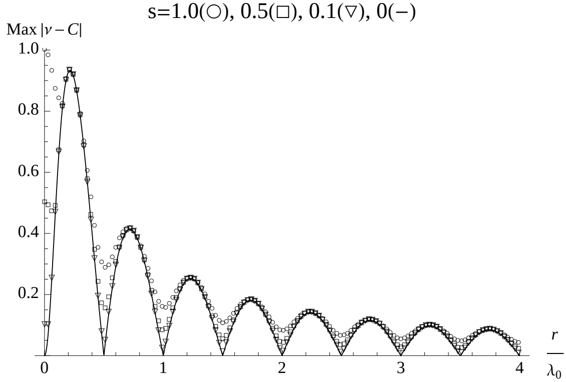
A measurement scheme for detecting the amount of entanglement in the atomic qubits pinned at given positions is studied by analyzing the interference pattern obtained when they emit scalar photons spontaneously [1].

In the case of two qubits, a well-known relation is revisited [2], in which the interference visibility is equal to the concurrence of the state in the infinite spatial separation limit of the qubits. For finite distances of two atoms, we study the maximal deviation between the visibility and the concurrence by taking into account the superradiant and subradiant effects. The figure below shows the discrepancy between these two quantities as a function of interatomic distance when the purity of the initial state is $1.0, 0.5, 0.1, 0$. The result indicates that this deviation is small whenever the qubits are separated by a distance which is a multiple integer of half the wavelength associated to the optical atomic transition.



In the case of three qubits, the relations between various entanglement measures and the interference visibility are studied by analyzing the spontaneous emission process from the W-like states to the ground state in the large separation limit of atoms. A qualitative correspondence among several entanglement measures and the interference visibility is discussed. In particular, it is shown that the visibility is directly related to the maximal bipartite negativity.

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Dark Resonances and All Optical Spin Manipulation of an NV Center in Diamond

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All optical manipulation of spin qubits is a useful tool in quantum control and quantum information science since it can be very fast and spatially selective at micrometer length scales. We demonstrate that the electronic spin of individual NV centers in diamond can be initialized, manipulated, and measured all optically. Our approach makes use of lambda-type two-photon transitions recently identified in NV centers[1,2]. We first show that optical pumping of dark resonances and coherent population trapping can be used as a method for initial state preparation of the electronic and nuclear spin. We further use off-resonant optical excitation of the lambda system to obtain unitary rotations of the electronic spin.

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Design of quantum Fourier transforms and quantum algorithms by using circulant Hamiltonians

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Quantum information processing is built upon sequences of special unitary transformations. One such transformation is the quantum (discrete) Fourier transform (QFT)[1]. QFT is a key ingredient of many quantum algorithms, including Shor's factoring algorithm[1],[2], the quantum phase estimation algorithm[1] and the discrete logarithms computing[1]. Therefore, in order to realize these algorithms, we need to have an efficient method for making QFT. Traditionally, the QFT is implemented by a quantum cirquit consisting of a large number of Hadamard gates and controlled phase shift gates.

We propose to construct QFT by using a special class of Hamiltonians, having a circulant symmetry. These Hamiltonians have the advantage that their eigenvectors are the columns of the discrete Fourier transform, and they do not depend on the particular elements of the Hamiltonian, as far as the symmetry is conserved. This important feature makes techniques based on circulant Hamiltonians robust against variations in the interaction parameters[3].

In order to realize QFT, we use a special time-dependent Hamiltonian $\mathbf{H}(t)$, which coincides with a circulant matrix at a final time t_f,

$$\mathbf{H}(t_f) = \mathbf{H}_f, \tag{2}$$

where $\mathbf{H}_f$ has a circulant symmetry. If we demand adiabatic evolution for our system, it will end in an eigenstate of the Hamiltonian, and it will realize the QFT. The Hamiltonian $\mathbf{H}(t)$ in the initial moment t_i is a diagonal matrix with energies that must not be degenerate:

$$\mathbf{H}(t_i) = \text{diag}(E_1, E_2, \ldots, E_N), \tag{3}$$

where N is the dimension of the Hilbert space we are using. In such way we ensure that the evolution is adiabatic and there are no nonadiabatic transitions between the adiabatic states.

Some systems, which could implement these circulant Hamiltonians (for $N = 4$), are the following. First, a $J = 1/2 \leftrightarrow J = 1/2$ system, interacting with two linearly polarized fields in perpendicular directions, the second one seen as a superposition of two circularly polarized fields (σ^+ and σ^-). Another possible system is the so called "diamond". It is a $J = 0 \leftrightarrow J = 1/2 \leftrightarrow J = 0$ system, interacting with two circularly polarized fields.

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A Quantum Turing Machine

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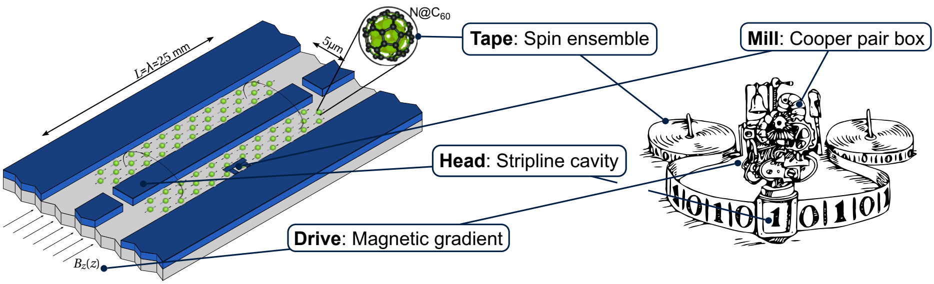
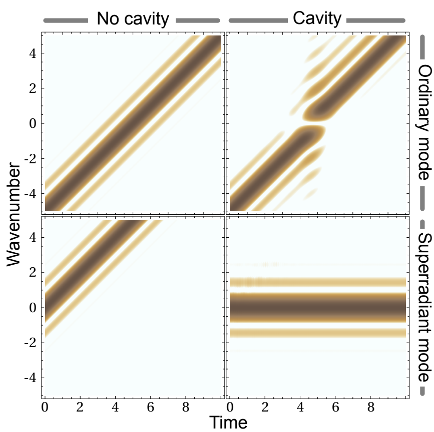


We study a recently proposed quantum information processing platform based on an electron spin ensemble coupled to a coplanar waveguide resonator[1]. We are particularly interested in the shear effect that is observed when a magnetic field gradient is applied to the spin ensemble while it is interacting strongly with the cavity, as illustrated in Fig. 2.

The shear effect should be observable in a number of physical systems where an inhomogeneously broadened ensemble of independent subsystems interact with a central system, and where the inhomogeneous broadening can be effectively inverted by e.g. spin echo techniques.

Figure 2: *The shear effect.*

The cavity interaction gives rise to an energy shift of the superradiant mode of the ensemble, which in effect isolates this particular mode from the ensemble dynamics. This modifies the evolution of spin waves as they pass through the region of wavenumber values close to that of the superradiant mode. For certain system geometries the disturbance does not lead to any diffusion in wavenumber space, but can be accurately described by a shear in the wavenumber evolution.



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Remote Spin Coupling and Room Temperature Quantum Computation in NV Diamond Centers

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We propose an experimentally feasible architecture for a room-temperature solid-state quantum computer utilizing nitrogen-vacancy (NV) defects in diamond as qubits and demonstrate the possibility of high fidelity operations. At an implantation spacing of 20nm, magnetic dipole-dipole interactions are sufficiently strong to enable coherent coupling of qubits. We further investigate remote spin coupling as a candidate for reducing the experimental constraints on such implementations. This approach makes use of a two-dimensional array of nitrogen impurities with sparsely implanted NV center qubits. By utilizing nitrogen impurities to mediate quantum state transfer, it is possible to coherently couple spatially separated qubits using SWAP gate, spin chain, and quantum mirror techniques. Finally, we show that perfect state transfer is possible through completely thermal spin chains of arbitrary length using only Hamiltonian evolution.

High efficient loading of two atoms into a microscopic optical trap by using a spatial light modulator

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We demonstrate a approach to transport two individual ^{87}Rb atoms trapped in a two-site ring lattice into a single microscopic far-off resonance trap (MFORT) by utilizing a spatial light modulator (SLM). We employ our recently developed technique of dynamically rotating computer generated ring lattice just through displaying the hologram animation movie on the SLM [1], then we transform ring lattice with $l = 1$ into a single microscopic dipole trap. Two atoms initially trapped in the ring lattice are brought into single MFORT under the evolution of the computer generated holographic dipole traps. Our scheme is simple for experimental implementation, and we obtained a success rate larger than 95% of preparing pairs of atoms in a single MFORT experimentally. Meanwhile, with two atoms in the MFORT we observed a strong two-atom loss upon imposing the resonant light.

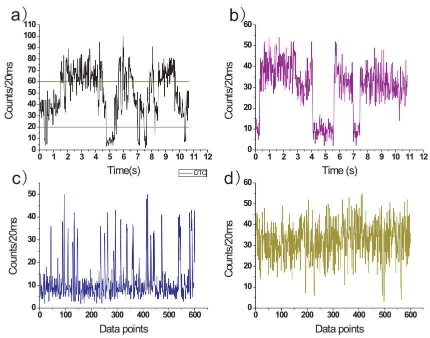

Figure 1: *Observed fluorescence of single atoms. Shown in (a) is the fluorescence signal from the whole two traps in the double well ring lattice . (b) is the fluorescence signal from atom in the single Gaussian trap. (c) is the accumulated fluorescence signal from single trap after two atoms trapped in the ring lattice being injected into single trap. (d) is the the accumulated fluorescence signal from single trap after single atoms trapped in either part of the ring lattice being inserted into the single trap.*

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Substantial interaction between a singe atom and a focused light beam

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We investigate both theoretically and experimentally the near-resonant interaction between a single atom in an optical dipole trap and a focused light beam. We have demonstrated that even for a moderate focusing strength, a single atom localized at the focus of a simple aspheric lens can scatter a significant fraction of light [1,2], impose a phase shift [3], and partially reflect a probe beam. With our current experimental system, we observe an extinction of 10%, a phase shift of about 1° and a reflectivity of 0.17%. For an optimal focusing geometry, we would expect an extinction up to 92%, and a phase shift of 30°. The strength of an observed effect together with the theoretical predictions suggests to combine the effects of strong focusing with the well-established methods of cavity QED. As an example one can consider a cavity which supports a strongly focused field mode of the type we obtain with our aspheric lens arrangement [4] (see Fig. 1).

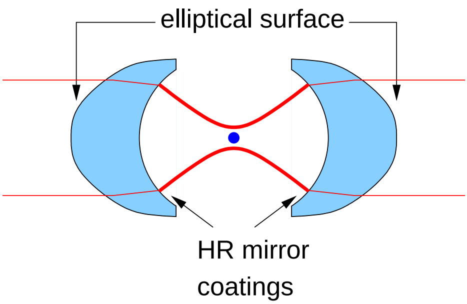

Figure 1: *Atom-cavity configuration in the strong focusing regime. Outer elliptical surfaces of the mirrors provides the mode coupling for a numerical aperture of up to 0.3.*

Simple estimates show that in such case one should achieve the single photon Rabi frequency few times larger than obtained in the current experiments [5,6] and thus be able to reduce the Q factor of the mirrors needed to compensate for the losses. This opens new perspectives in possibility to scale up the system consisting of many 'atom+cavity' nodes for quantum networking due to a significant technical simplification of the atom-light interfaces.

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Quadripartite continuous-variable entanglement via quadruply concurrent downconversion

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We investigate an experimentally feasible intra-cavity coupled down-conversion scheme to generate quadripartite entanglement using concurrent nonlinearities. We verify that quadripartite entanglement is present in this system by calculating the output fluctuation spectra and then considering violations of optimized inequalities of the van Loock-Furusawa type[1]. The entanglement characteristics both above and below the oscillation threshold are considered. We also present analytic solutions for the quadrature operators and the van Loock-Furusawa correlations in the undepleted pump approximation. Currently, we are investigating a similar scheme[2] as a candidate for realizing the simplest four node cluster state, proposed as a resource for one-way quantum computing.

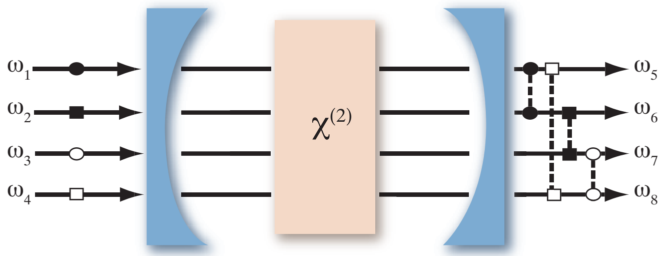

Figure 1: *Schematic of a $\chi^{(2)}$ crystal inside a pumped Fabry-Pérot cavity. Pump lasers drive four intracavity modes with frequencies ω_1, ω_2, ω_3 and ω_4 (represented by circles and squares), which are down-converted to four output modes with frequencies ω_5, ω_6, ω_7 and ω_8.*

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Novel Control of Atom-Atom Interactions in a Two-Way Cascaded Cavity QED System

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We present an investigation of a two-way cascaded cavity QED system consisting of two microtoroidal resonators, which are connected via an optical fibre. The microtoroids act as cavities, each with two counter-propagating whispering-gallery modes, and single atoms are coupled to each of the microtoroids through the evanescent fields leaking from these modes. In the bad cavity regime, where the decay rate of the resonator modes is much larger than any other rate in the system, a simplified master equation with the resonator modes adiabatically eliminated is derived. From this master equation, we uncover a novel dependence of the effective atom-atom interaction (mediated by the cavities and fibre) on the atom-cavity detuning. In particular, with appropriate choices of detunings the atoms can be made to experience either collective spontaneous emission (superradiance) or a (coherent) dipole-dipole interaction with single-atom spontaneous emission. This capacity for switching the fundamental nature of the interaction seems unique to the two-way cascaded system considered and is manifested in the spontaneous emission spectrum.

Ground-state Quantum Beats in Cavity QED

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We present measurements of optical correlations from a driven high-finesse cavity traversed by a continuous cold beam of 85 Rb atoms. The combination of two modes of orthogonal light polarization with the magnetic structure of the atoms allows us to separate photons originating from spontaneous emission from those that come from the driving laser. The second-order intensity correlation function reveals quantum beats at twice the ground-state Larmor frequency for a small applied magnetic field. The beats arise from ground-state superpositions generated in the spontaneous emission cycles, between magnetic sublevels in a single atom, and between the levels of multiple atoms. In addition, the mixing in of a small amount of coherent drive light before detection allows us to measure a homodyne contribution at the single Larmor frequency. The coherences survive many cycles of spontaneous emission and optical pumping. The frequency of oscillation is sensitive to different parameters of the system; we report a power-dependent accumulation of phase from sponanteous emission events that exactly reverses the sign of the normal AC Stark shift in the ground state. We present the results of modeling the atomic beam and interactions in a quantum trajectories simulation with the full magnetic structure and many simultaneous atoms, and from this extract the form of the various coherent processes that make up the averaged signal. Work supported by NSF of the USA, CONACYT Mexico, and the Marsden Fund of the RS of NZ.

Quantum phase transition of nonlinear light in the finite size Dicke Hamiltonian

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We study the quantum phase transition of a N two-level atomic ensemble interacting with an optical degenerate parametric process, which can be described by the finite size Dicke Hamiltonian plus counter-rotating and quadratic field terms. Analytical closed forms of the critical coupling value and their corresponding separable ground states are derived in the weak and strong coupling regimes. The existence of bipartite entanglement between the two-level-system ensemble and photon field as well as between ensemble components for moderate coupling is shown through numerical analysis. Given a finite size, our results also indicate the co-existence of squeezed fields and squeezed atomic ensembles.

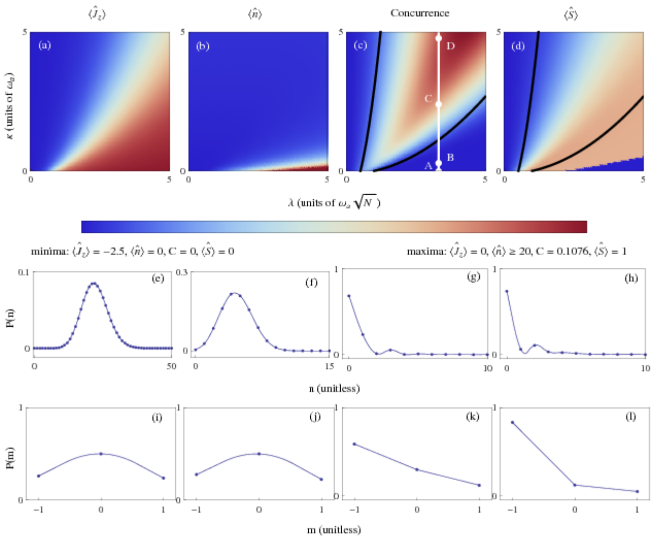

Figure 1: *Phase diagram of the studied Hamiltonian,* $\hat{H} = \hbar\omega_f \hat{a}^\dagger \hat{a} + \hbar\omega_a \hat{J}_z + \hbar\frac{\lambda}{\sqrt{N}}(\hat{a} + \hat{a}^\dagger)\hat{J}_x + \hbar\kappa(\hat{a} + \hat{a}^\dagger)^2$*, in the parameter space of the linear photon-atom coupling strength,* λ*, and the nonlinear photon-photon interaction strength,* κ*. (a) The mean value for the atomic z-component,* $\langle \hat{J}_z \rangle$*, (b) the average photon number for the field,* $\langle \hat{n} \rangle$*, (c): the bipartite concurrence, and (d) the entropy of entanglement,* $\langle \hat{S} \rangle$*, are calculated for the case of* $N = 2$*. The corresponding minima and maxima values for the color legend are shown below. The field photon number and atomic angular momentum probability distributions along the solid line in (c) are shown in (e-h) and (i-l), ordered according to the markers* A*-*D*, respectively.*

Entanglement between internal and external degrees of freedom of a driven trapped atom

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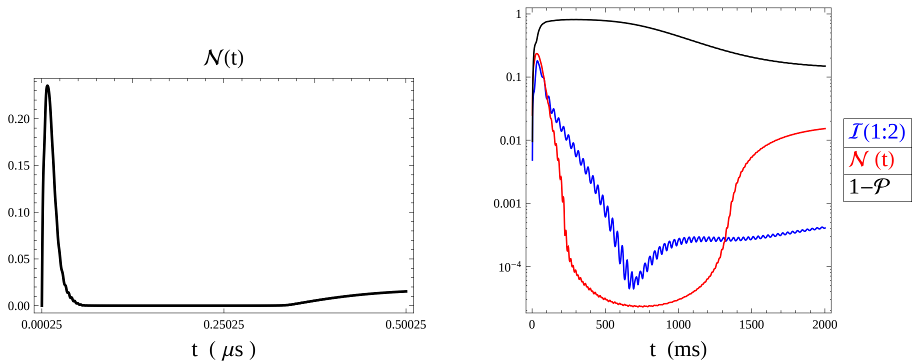
The dynamics of a Λ-shaped trapped atom, driven by two lasers to conditions approaching electromagnetically-induced transparency (EIT), is studied numerically via the quantum Markovian master equation[1,2]. The analysis of the solutions of this equation allows to investigate the nature of dissipative processes which are responsible for *EIT* cooling[3].

The numerical approach gives us the possibility to investigate the dynamics of the entanglement between electronic and vibrational degrees of freedom and the quantum mutual information. Far from the Lamb-Dicke limit an intricate behavior of these quantities is found, as well as the emergence of a mixed entangled non-equilibrium stationary state[4]. An example of our numerical calculations is shown in Fig. 1. The initial conditions ($t = 0$) is that the atom is in electronic state $|1\rangle$ and in vibrational level $n = 5$. After 3 ms the mean vibrational quantum number of the atom is $\langle n \rangle = 0.02$. During the cooling process the death and revival of negativity is observed. Moreover, the numerical simulation allows the determination of the degree of non-Markovianity of the dynamics[5].



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Using noise to improve atom-cavity coupling

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Most of the time, noise and the consequent decoherence are considered villains to the observation of fundamental quantum aspects and the production of quantum devices. In this work[1] we present a counter-example with very interesting potential applications both in cavity QED and nanophotonics. First, we describe in general terms the dynamics of an incoherently and off-resonantly pumped single emitter coupled to a cavity field in the presence of pure dephasing and dissipation. Then we analyze this system both when it is dominated by spontaneous emission and when stimulated emission plays a crucial role.

In the first scenario, we show that the two systems behave like two quantum boxes exchanging excitations and we derive an effective coupling constant for this exchange that depends on both their coherent and incoherent properties. This effective rate then defines a generalized Purcell factor for the atom which is also essential to determine the rate of emitted photons in the cavity mode if the atom is continuously pumped. Both quantities are maximized when atom and cavity are in resonance, i.e. any detuning acts negatively on both of them. However, we show that if the two systems are detuned, the addition of pure dephasing noise can partially compensate for the off-resonance effect improving the system's capacity to generate single photons on demand.

In the second scenario, we consider an atom that is strongly pumped and also coherently exchanges photons with the cavity field. We show that ideal single emitter lasing conditions are achievable in resonance, and detuning tends to spoil them. However, in the presence of detuning, once again, pure dephasing comes to the rescue, helping restoring the lasing regime.

The formalism developed is general and can be applied to any system composed of a two-level oscillator and a cavity field, be it in atomic or superconducting CQED, solid state nanophotonics, and so on. The general conclusion is that noise and decoherence can also play positive roles in such systems allowing for the study of fundamental physics and the development of new and more efficient quantum devices.

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Multi-Photon Blockade in Cavity QED

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The driven Jaynes-Cummings model is studied in the strong-coupling, strong-drive regime by way of numerical simulations. The investigation is motivated by recent advances from Circuit QED which show conclusively that the model and parameter regimes considered are experimentally feasible. The focus is on the multi-photon transitions to higher excitation dressed-states, as observed by Bishop *et al.*[1]. Photon statistics of the light leaking out of the cavity are examined when the laser is tuned to such a multi-photon resonance. We find that with increasing drive strength, bunched, super-poissonian light is transformed into antibunched and sub-poissonian light. These results are interpreted and a simple model is constructed to explain our observations analytically. Moreover, the incoherent spectrum is computed, leading to observation of a saturation effect and multiple dynamic Stark splittings, resulting in a Mollow triplet. This is interpreted analogously to resonance fluorescence in the context of Floquet theory and the simplest example is treated analytically. In summary, we observe Multi-Photon Blockade.

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Strong Interactions of Single Atoms and Photons near a Dielectric Boundary

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Strong coupling in cavity quantum electrodynamics (cQED) between atoms and microtoroid resonators[1] allows for coherent interactions between matter and light to dominate over irreversible channels of dissipation in a scalable on-chip quantum node with high photonic coupling[2]. Using such microresonators as nodes in a quantum network suitable for large-scale quantum information processing[3] necessitates localizing individual atoms on distance scales $\sim$100 nm from a resonator's surface where atoms experience significant van der Waals interactions with the dielectric boundaries of the resonator. Here, we study the dynamics of cesium atoms strongly coupled to a microtoroidal cavity in a regime where atomic motion is influenced by surface interactions with the dielectric resonator. We utilize fast logic electronics to achieve real-time detection in 250 nanoseconds of falling atom transit events of duration 2-4 microseconds followed by conditional switching of the cavity input beam while the atom is coupled to the cavity. Laser probe detuning after atom detection enables measurement of the cQED response in both the temporal and spectral domains, allowing observation of vacuum Rabi splitting. We employ these strong atom-cavity interactions to probe the significant role of van der Waals attraction on the motion of an atom through the evanescent field of the resonator. Our work offers a first step toward trapping atoms near the surface of micro- and nano-scopic optical resonators for applications in quantum information science.

We thank NSF, the DoD NSSEFF program, ARO, and IARPA for financial support.

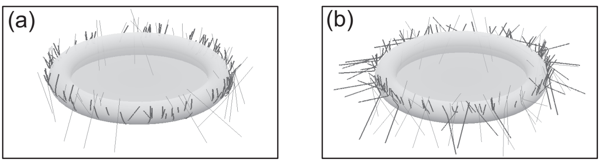

Figure 1: *Simulated trajectories transiting by a microtoroid for probe frequency (a) red-detuned and (b) blue-detuned from the atomic transition. For red detuning, all detected atoms crash into the dielectric surface due to dipole and van der Waals attraction, while for blue detuning some are deflected by the dipole force.*

[1]D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala. "Ultra-high-Q toroid microcavity on a chip." *Nature* **421**, 925-928 (2003)

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Multipartite entanglement production using feedback

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The production and manipulation of entangled states has been a major feature of quantum information research in the last several years. A problem with producing entangled states is that decoherence can quickly destroy entanglement. A promising approach to deal with this problem is the use of active quantum feedback control. Recently, we have shown that direct feedback under the appropriate detection strategy leads to the robust production of highly entangled states of two atoms or ions in a cavity[1,2]. In this contribution we will present our recent progress towards the extension of this model to multipartite systems.

The system we investigate consists of a chain of two-level atoms equally coupled to a single cavity mode (Fig. 1). The atoms are simultaneously driven by a laser field (not shown) and a photo-detector monitors the leakage of photons from the damped cavity. Every detection event triggers the application of a control Hamiltonian on the atoms.

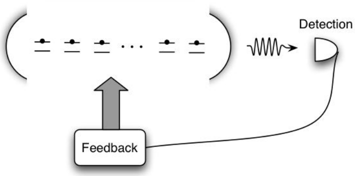

Figure 1: *Schematic view of the system.*

It was shown in[1] that a quantum jump-based feedback can stabilise the anti-symmetric Bell state against different decoherence sources. When more atoms are added, the symmetry structure gets more complex but control can still be performed on the system. For even number of atoms, there are various pure states that are dark states of the system. Due to the multiplicity of stationary states, the system without control, converges to a mixture of these states that is not necessarily entangled. The inclusion of a suitable choice of unitary control is able to isolate the desired entangled state as the only stationary solution of the problem. With appropriate choice of feedback the maximum steady state concurrence achieved is around 1.28, slightly below the value of 1.32 for a 4-partite GHZ state. With six or more particles the steady states have entanglement greater than the corresponding GHZ state.

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Cavity QED with single defects in diamond: strong coupling using superconducting resonators

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Circuit-QED has demonstrated very strong coupling between light and matter and has the potential to engineer large quantum devices [1]. Hybrid designs have been proposed which couple large ensembles of atomic and molecular systems to the superconducting resonator [2]. We show that one can achieve an effective strong coupling between light and matter for much smaller ensembles (and even a single electronic spin), through the use of an interconnecting quantum system: in our case a persistent current qubit [3]. Using this interconnect we show that one can effectively magnify the coupling strength between the light and matter by over five orders of magnitude $g \sim$ 7Hz $\rightarrow$ 100kHz, and enter a regime where a single Nitrogen-Vacancy electronic spin can shift the cavity resonance line by over $\sim$ 20 linewidths. With such strong coupling between an individual electronic spin in an NV and the light in the resonator, one has the potential build devices where the associated NV nuclear spins can be strongly coupled over centimeters via the superconducting bus.

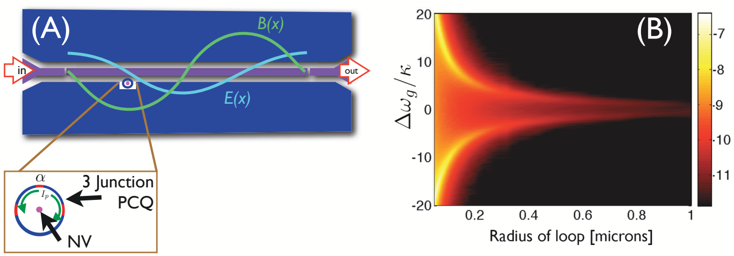

Figure 1: *Strong coupling of a single Nitrogen-Vacancy electronic spin to a microwave photon trapped in a superconducting coplanar resonator. (A) Schematic of NV encircled by a Persistent Current Qubit (PCQ) next to a coplanar resonator, (B) Cavity spectrum indicating the splitting of the resonance lines due to the NV as one shrinks the PCQ loop.*

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Quantum Non-Demolition Measurement in a Radio-Frequency High Density Atomic Magnetometer

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Quantum Non-Demolition (QND) measurements have attracted a great deal of interest for extending the precision of measurements beyond the standard quantum limits. We implement and study a QND scheme in a radio-frequency atomic magnetometer, operated at high density with hot ^{39}K vapor. A circularly polarized pump beam polarizes alkali atoms along the direction of a static holding field, and a perpendicular linearly polarized probe beam measures the amplitude of spin precession through Faraday paramagnetic rotation. In this scheme, the back-action is generated as a result of the probe beam light-shift noise. We use a stroboscopic probe beam that turns on and off at twice the Larmor frequency to realize a quantum non-demolition Hamiltonian in a manner similar to the one that has been implemented with mechanical oscillators[1]. We show back-action suppression with this method that depends on the duty cycle of the probe beam and on the detuning of the modulation frequency from twice the Larmor frequency. We study how the spin-projection noise depends on the longitudinal polarization and demonstrate very good agreement with a simple theoretical model. We find that the unpolarized spin noise offers an excellent standard to calibrate the polarized spin noise and exclude potential non-quantum mechanical noise sources. We also discuss a situation where the sensitivity of a magnetometer will benefit from the increased bandwidth that QND measurements offer[2]. In particular, in high density alkali-metal vapors the magnetic sensitivity of an initially fully polarized sample decreases with time as the transverse relaxation due to spin-exchange collisions between alkali atoms increases. The high bandwidth of the QND magnetometer should allow us to operate efficiently at short timescales, where the magnetic sensitivity is maximized. We finally show preliminary results of spin-noise measurements in a multi-pass cell. Unlike a cavity, it has a large active volume and is very robust and easy to implement. We demonstrate spin noise measurements with 38 passes with corresponding increase in the spin noise relative to the photon shot noise. This multi-pass arrangement increases significantly the optical depth and offers the possibility of higher magnetic field sensitivity and stronger squeezing.

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Cavity-Assisted Nondestructive Measurement of Rabi-Oscillations

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The coherent interaction between a quantum-mechanical two-level system and electromagnetic fields is the basic ingredient of most quantum optical experiments. Applications like atomic clocks directly rely on the observation of Rabi-oscillations of an atomic ensemble induced by microwave radiation. These oscillations are routinely observed in a large variety of quantum systems. However, measurement backaction usually destroys the coherence of the system, and the oscillations can not be observed in a single run. Therefore, a large number of experimental repetitions is required to reconstruct the full oscillation. Recently, the nondestructive observation of Rabi-oscillations has been demonstrated using large ensembles of approximately 10^6 cold Cs atoms[1,2].

In our experiment we use a fiber-based high-finesse cavity on an atomchip[3] to directly observe Rabi-oscillations between the two ground state hyperfine states of small ensembles containing less than 1000 ultracold ^{87}Rb atoms. We investigate the transition from the 'classical' regime, where we non-destructively observe the Rabi-oscillations of a few 100 atoms, to the quantum regime, where the oscillations are suppressed due to the quantum Zeno effect.

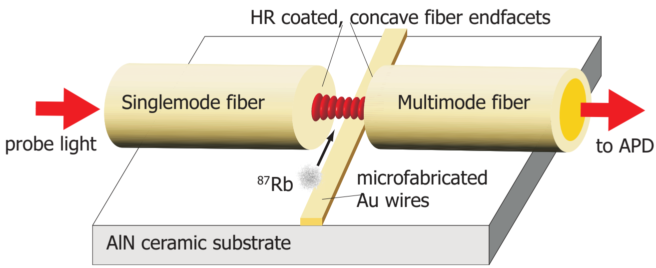

Figure 1: *Experimental setup. A microfabricated fiber cavity on an atomchip. To prepare atomic ensemble inside the cavity, we first generate a small BEC and magnetically transfer it into an intracavity standing wave dipole trap. The cavity transmission depends on the difference of atomic population in the two hyperfine states allowing the direct observation of Rabi-oscillations.*

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Itinerant Ferromagnetism in Cold Fermionic Atoms Loaded on a Two-leg Optical Ladder

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It has been known, in the field of correlated electron systems, that the way in which correlation effects appear is dominated by the lattice structure. One such quantum phase is itinerant ferromagnetism, for which a full understanding is yet to come, so that the cold fermionic atom systems are an ideal test-bench. Three mechanisms have been known for itinerant ferromagnetism, i.e., Stoner's, Nagaoka's, and flat-band mechanisms[1]. The first one has been reported in an ultra-cold atom experiment recently[2], while the latter two, mutually related, have not been realized. Realization of the flat-band ferromagnetism, arising in dispersionless bands with some topological condition, in optical lattice systems is a challenging problem[3][4]. However, the lattice structure required for the flat-band is not so simple. Nagaoka's ferromagnetism, on the other hand, requires less stringent lattice conditions, but the ferromagnetism in its original formalism requires a pathological condition, i.e., a single hole in a half-filled band. One manifestation of the pathology is the fragility of Nagaoka's state against thermal fluctuations. Subsequently, Nagaoka-related ferromagnetism has been explored for special lattices such as the two-leg ladder that accommodates finite hole densities and a finite energy gap for the magnetism[5].

With this background, here we propose that a stable itinerant ferromagnetism should emerge in cold fermionic atoms for finite hole densities in a two-leg ladder optical lattice system[6]. A special interest in the cold atom system is that, on top of the optical lattice potential which should be readily created by a combination of superlattice standing waves of lasers, the atoms feel a trapping potential. This causes the system to have an interesting phase separation into magnetic and nonmagnetic phases in real space. We discuss how to create and detect the itinerant ferromagnetism in this system, including spin-imbalance effects. Specifically, we predict that the system should exhibit the phase-separated magnetism in spin-imbalanced situations, and the phase diagram obtained here shows that the required strength of correlation is also realistic. So the ferromagnetism is expected to be observable in ultra-cold atom experiments.

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Simulation of quantum noise in BEC

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Atom interferometry is at the heart of many suggested future applications of ultracold atomic physics. Bose-Einstein condensates or atom lasers have potential advantages as detectors or sensors, provided one can extract atomic phase information. However, unlike photons, atoms can interact rather strongly, causing dephasing. An intimate understanding of quantum many-body dynamics is essential in understanding the precise nature of interaction-induced dephasing in the measurement process. Progress in this technology therefore requires a quantitative theory of atom interferometry.

Coupled Gross-Pitaevskii equations are widely used to simulate the dynamics of BEC. This method is easy and relatively fast, and it allows one to obtain rather accurate predictions for the evolution of the cloud structure[1]. The problem is that this method produces incorrect results for low number of particles or long evolution times, since it neglects quantum noise. There are ways to improve GPE-based simulations, one of which is the inclusion of quantum noise terms via the Wigner representation.

Here, we give a simple, yet quantitatively accurate theoretical approach to calculations of atom interferometry using a truncated Wigner representation. This method extends the conventional Gross-Pitaevskii equations describing a Bose condensate to include quantum noise effects. We show through comparison with experimental interferometric measurements on Bose condensates that the theory predicts observed dephasing results, within experimental errors. No fitting parameters or added technical noise is required in these comparisons. Importantly, we can clearly demonstrate where phase decay is driven by intrinsic quantum fluctuations due to the effects of a beamsplitter, and where it is driven by trap inhomogeneity or other effects.

The noise can be taken into account by writing the master equation for the condensate and transforming it into one of the quasi-probability representations, like positive-P[2,3] or Wigner[2]. The resulting equation can then be expressed as a set of stochastic equations, which can be solved numerically. We present the results of such simulations for several types of experiments on ^{87}Rb condensates (namely, two-component clouds of $|1,-1\rangle$ and $|2,-1\rangle$ states in a magnetic trap). In addition, we use the simulation data to revise the values of scattering lengths and loss terms for these components.

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Single-Site Probing of the Superfluid-Mott Insulator Transition with a Quantum Gas Microscope

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Ultracold gases in optical lattices provide an elegant avenue to controlled, coherent interactions between atoms, especially for the realization of strongly correlated phases of matter. These systems can faithfully mimic the physics of condensed materials under much more dilute conditions, permitting more precise control over interactions and potentials as well as new and unique probes of the resulting ordering.

Here we present the first site-resolved study of the superfluid-Mott insulator transition. Using a Quantum Gas Microscope, we are able to observe, with single-site resolution, the shell structure of the Mott insulator, with up to $N = 4$ atoms per site. Our high single-shot fidelity permits us to observe atom number statistics in a site-resolved manner, a tool which we employ to demonstrate squeezing of the atom number distribution by more than a factor of 10 beyond the shot-noise limit. We then investigate the timescale of the SF-MI transition using the degree of squeezing as a probe, and observe a squeezing-adiabaticity timescale of approximately 3 ms, consistent with the interaction U, and not the tunneling J as one might naïvely expect.

Ultra-low entropy domains seem to be an important first step towards realization of quantum magnets in ultracold atomic systems. To this end, we present evidence of ultra-low entropy Mott domains realized as heterostructures in contact with superfluid baths.

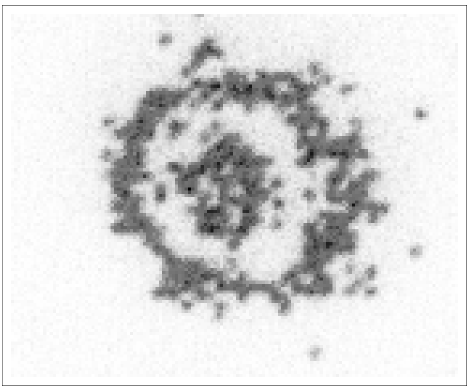

Figure 1: *Single-shot, site-resolved image of a Mott Insulator with shells of up to* $N = 3$ *atoms per site. Our imaging method is sensitive to the parity of the site occupation, so* $N = 1, 3$ *appear black (i.e. scatter light), and* $N = 2$ *appears white (i.e. do not scatter light).*

Versatile Optical Lattices to Control Rydberg Atom Interactions for Uses in Quantum Computing.

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The long lived quantum levels in the hyperfine manifold of neutral atom ground states have long been candidates as qubits for quantum information protocols. However, neutral atoms have very short range interactions, so the use of Rydberg atoms, with relatively long range interactions ($\sim 10\mu$m), can be used to mediate interactions between qubits. Recent experiments with Rydberg atoms have demonstrated entanglement[1] and the implementation of a controlled-NOT gate[2].

We propose a scheme to create versatile optical 2D lattices using a scanning beam trap[3] that allows controlled interactions between Rydberg atoms located at different lattice sites. The scanning trap involves rapidly moving a tightly focused laser over several positions, so that the atoms see a time-averaged potential. The scanning trap position is controlled using a 2D acousto-optic modulator. The atoms are effectively trapped in a 2D array of optical tweezers, the structure of which can be dynamically changed to bring together, and allow interactions between atoms that are not located adjacent to one another in the lattice. The flexibility of this system will allow individual control of a single lattice site allowing more efficient coding schemes and more refined control over a large number of atomic qubits.

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Search for biomagnetism with a sensitive atomic magnetometer

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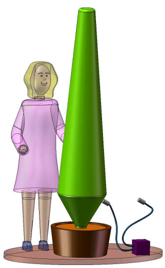
The detection of biological magnetic signals has added a new dimension to the understanding of physiological and biological processes[1]. Superconducting quantum interference device (SQUID) magnetometers have been leading the field of ultra-sensitive magnetic field measurements[2]; however the area of resonant magneto-optics and atomic magnetometry has experienced a resurgence driven in particular by new techniques in producing dense atomic vapors with long-lived polarized ground-states. Atomic magnetometers have now achievied sensitivities surpassing that of SQUIDs[3] and, in contrast to SQUIDs which measure magnetic flux and require cryogenics, atomic magnetometers operate at room temperature and measure the absolute magnetic field.

Plant bio-processes span several minutes to several hours and the expected magnetic field from such processes is small. We select the Titan arum *(Amorphophallus titanum)* inflorescence known for its fast bio-chemical processes while blooming and we report what we believe is the first (null) measurement of plant bio-magnetism with a sensitive atomic magnetometer (Geometrics G858). We show that the upper bound for the surface magnetic field from these processes is less then $\sim$0.6 μG. Prospects for more sensitive measurements will be presented.



The titan arum (*Amorphophallus titanum*), nicknamed ‘Trudy’, in full bloom on June 23, 2009, at the University of California Botanical Garden. The Geometrics G858 atomic magnetometer sensors are positioned behind the plant.

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

Transformation from EIA into EIT by incoherent pumping in ^{85}Rb D_1 line

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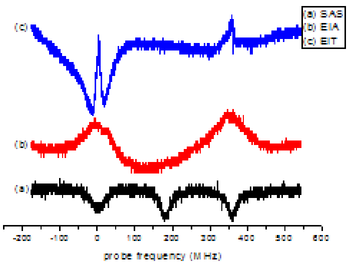
In open systems of ^{85}Rb D_1 line, we have observed electromagnetically induced absorption(EIA) using two coherent laser fields [1]. Transformation from EIA into electomagnetically induced transparency(EIT) by adding a pump laser beam, which is incoherent with coupling beam, is occurred as Figure 1. Absorption spectra were observed depending on intensities and polarizations of each laser beams and transition lines. However, in a closed system of ^{87}Rb D_2 line, this transformation was not found in Figure 2. We report an experimental observation of such transformation in an Rb vapor cell.



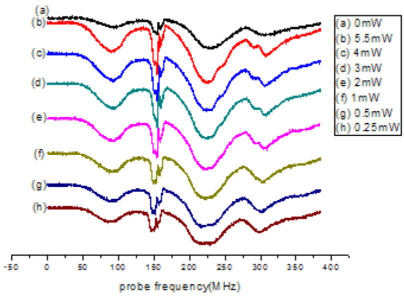


Figure 1: *Absorption spectra of the transition F=3→F'=2,3 in the open system of ^{85}Rb D_1 line. Transformation is happened by adding pump laser.*

Figure 2: *Absorption spectra of the transition F=3→F'=3,4 in the closed system of ^{87}Rb D_2 line. EIA is not changed to EIT when adding the pump laser.*

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Isotope shifts and hyperfine structure of the Fe I 373.7 nm resonance line

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We report the observation of ultrahigh resolution spectra of resonance lines in Iron atoms. The spectra have been recorded using the saturated absorption laser spectroscopy technique combined with lock-in amplification of the signals. The experimental arrangement is illustrated in Fig. 1. The resolution $\lambda/\Delta\lambda$ of the reported lines is of the order 60 millions and allows a neat observation of the optical isotope shifts of the transition $3d^6 4s^2\, {}^5D_3 \rightarrow 3d^6 4s4p\, {}^5F^o_4$ at 373.7 nm for the 4 natural iron isotopes ^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Fe. All those shifts have been measured using frequency markers generated with a Fabry-Perot interferometer. Among the 4 natural isotopes, ^{57}Fe is the only one to have a nuclear spin and to present consequently an hyperfine structure. This hyperfine structure has been measured using enriched samples of this particular isotope. First results about the hyperfine constant A of the upper level $3d^6 4s4p\, {}^5F^o_4$ will be presented. The authors thank the belgian F.R.S.-FNRS for financial support.

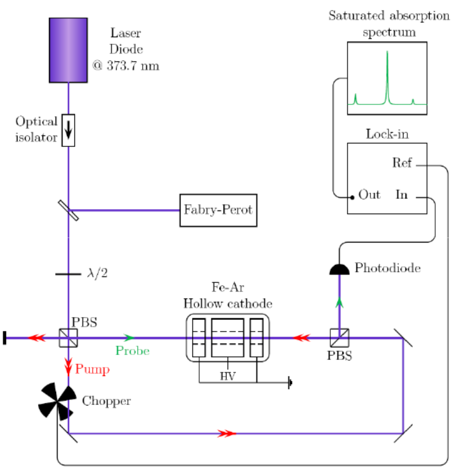

Figure 1: *Experimental arrangement used for the observation of Doppler-free saturated absorption spectra of the 373.7 nm resonance line in neutral iron.*

Zero-field nuclear magnetic resonance with parahydrogen induced polarization

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Nuclear magnetic resonance (NMR) is a powerful analytical tool for elucidating molecular structure and function. Conventionally, NMR is detected using inductive pickup coils in large magnetic fields, necessitating expensive and immobile superconducting magnets. The development of sensitive low-frequency magnetic field detectors such as superconducting quantum interference devices or atomic magnetometers reduces the need for such superconducting magnets, and has sparked considerable interest in NMR and magnetic resonance imaging in low values of the magnetic field.

One of the key parameters extracted from NMR spectra to determine molecular structure are scalar spin-spin couplings (an interaction of the form $J\mathbf{I}_1 \cdot \mathbf{I}_2$). Recently, we have demonstrated that such couplings can be detected in zero-magnetic field using microfabricated atomic magnetometers[1] using permanent magnets to pre-polarize a sample. In addition to eliminating superconducting magnets, the benefits of working in zero magnetic field include extremely high field homogeneity, both spatially and temporally, allowing narrow lines (we have demonstrated 100 mHz lines without employing spin-echoes) and very accurate determination of coupling parameters.

More recently we have demonstrated that parahydrogen, the singlet state of H_2, can be used to produce observable magnetization at zero magnetic field without the use of any prepolarizing magnet. Figure 1 shows the zero field J-spectra of natural abundance ethylbenzene polarized via hydrogenation of styrene with pH_2. For comparison, the expected signal from ethylbenzene prepolarized in a 2 T magnetic field would be below the noise level. New results on zero field decoupling sequences and multi-dimensional spectroscopy will also be presented.

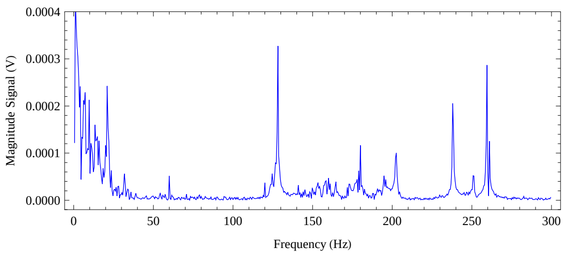

Figure 1: *Zero field J-spectra of ethylbenzene, polarized via parahydrogen.*

[1]M.P. Ledbetter, C.W. Crawford, A. Pines, D.E. Wemmer, S. Knappe, J. Kitching, D. Budker, "Optical Detection of NMR J-Spectra at Zero Magnetic Field", Journal of Magnetic Resonance **199**, 25-29 (2009).

Precision spectroscopy of atomic helium 2^1S_0 - 2^1P_1 transition

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The laboratory experiments of helium are important due to helium is the simplest two-electron neutral atom and it is one of the major elements in the Universe. Besides, the measurements of absolute frequencies and the isotope shifts of atomic helium transitions are useful tests of the theoretical calculations[1].

We have started a research project on the precision spectroscopy of 2^1S_0 - 2^1P_1 transition of atomic helium using a 2 μm single-frequency tunable laser. This laser is a diode-pumped Tm,Ho:YLF laser. A VBG (volume Bragg grating) is used as the wavelength tuning element and the output coupler of the laser cavity as well. The 2^1S_0 - 2^1P_1 transitions of ^{3}He and ^{4}He will be studied by the saturation absorption spectroscopy and their absolute frequencies will be measured using an optical frequency comb. In the end the isotope shift and hyperfine structure of ^{3}He will be determined accurately.

In this poster, we will present the schemes of 2 μm single-frequency tunable laser, Doppler-free saturated absorption spectroscopy of 2^1S_0 - 2^1P_1 transition in atomic He and the optical frequency comb. We will also discuss how to analyze the hyperfine levels $2^1P_{1,1/2}$ and $2^1P_{1,3/2}$ of ^{3}He, as shown on Figure 1.

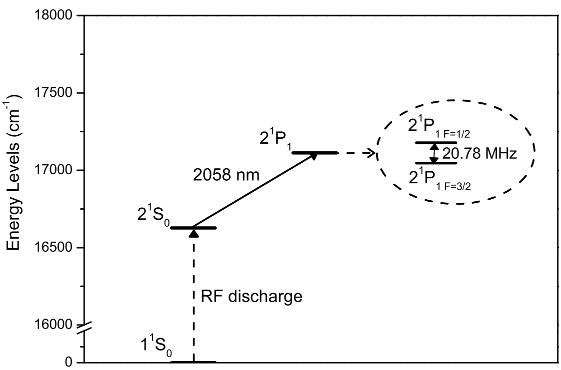

Figure 1: *Energy levels of 2^1S_0 - 2^1P_1 transition of ^{3}He*

[1]D. C. Morton, Qixue Wu, and G. W. F. Drake, " Energy levels for the stable isotopes of atomic helium (^{4}He I and ^{3}He I).", Can. J. Phys. 84, 83-105 (2006).

Observation of a Frequency-Shift in a Rb Absorption Spectrum using an Optical Nanofibre in a Vapour Cell

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In recent years, tapered optical fibres with subwavelength diameters, fabricated using a direct-heating technique[1], have attracted considerable research attention as tools for trapping and manipulating neutral atoms. Previously, we have shown that they are ideal tools for probing magneto-optical trap characteristics by coupling photons from a laser-cooled cloud of rubidium atoms into the guided mode of a nanofibre.[2] Conversely, atoms can absorb photons from the guided mode via an evanescent field when light of a wavelength comparable to the waist diameter of the nanofibre propagates through it.

In this work, we present recent experimental results whereby surface interactions of a rubidium vapour with a nanofibre were investigated. The frequency of a transmitted probe beam is scanned over a reference spectrum as a vapour is added to the cell. A red-shift of ∼50 MHz, due to van der Waals interactions, is clearly dominant in the nanofibre spectrum with respect to the reference signal which was recorded simultaneously (Fig. 1). Future work will involve incorporating a whispering gallery mode resonator into the setup, via coupling with the nanofibre, to further enhance the sensitivity of the system for bio-sensing applications.

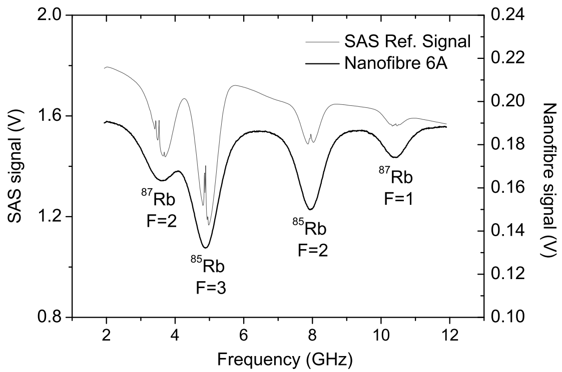

Figure 1: *Absorption signal through an optical nanofibre, transmission ∼2%, for the D2 lines in ^{85}Rb and ^{87}Rb with respect to a reference saturated absorption signal.*

[1]J.M. Ward, D.G. O'Shea, B.J. Shortt, M.J. Morrissey, K. Deasy and S. Nic Chormaic, Rev. Sci. Instrum. **77**, 083105 (2006).

[2]M. Morrissey, K. Deasy, Y. Wu, S. Chakrabarti and S. Nic Chormaic, Rev. Sci. Instrum. **80**, 053102 (2009).

Separating krypton tracers from air samples for ultra sensitive collinear fast beam laser spectroscopy

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^{85}Kr is a long lived radio-isotope ($T_{1/2}$=10.7 years) which is being used as a tracer in gas and oil reservoirs, since it does not occur naturally. We describe our laser spectroscopy apparatus together with a method for isolating the tracers in the samples and measure krypton isotope ratios.

We developed a portable apparatus for collecting, separating, and enriching of krypton from environmental air samples. The device is mainly based on cryogenic trapping of the gases at liquid nitrogen temperature on traps. In particular, the apparatus consists of a molecular sieve trap for the elimination of H_20 and CO_2, charcoal traps for the collection of krypton and other gases and three stages of gas chromatography to achieve separation and purification of krypton from mainly N_2, O_2, and Ar. Spurious residual N_2 and other reactive gases still remaining after the third stage of chromatography are removed at the final stage on a hot Ti sponge getter. A thermal conductivity detector is used to monitor the characteristic elution time of the various components of condensed gases in the traps after warming the traps from liquid nitrogen gradually to boiling water temperatures. This allows optimizing the switching time of the valves between the three stages of gas chromatography in such way that mainly krypton is selected and loaded to the next stages while removing the other gases to the exhaust using He gas for transportation. The krypton separation efficiency is determined using a residual gas analyzer and will be given for a variety of samples.

This research is supported by the Qatar Foundation under the NPRP grant 30-6-7-35 [1]

[1]R. Nava, H. Schuessler, M. Fahes, H. Nasrabadi, and A. Kolomenski, SPE Annual Technical Conference and Exhibition, 4-7 October 2009, New Orleans, Louisiana, SPE 124689.

High selectivity and sensitivity time of flight mass spectroscopy of Xenon tracers

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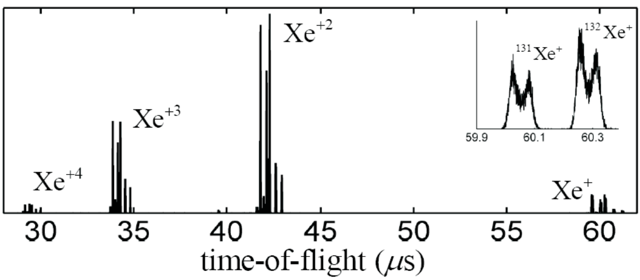
A reflectron type time-of-fight ion mass spectrometer has been developed to measure xenon isotope ratios. In this work, Xe ions were produced by irradiating target neutral atoms with radiation from a near terawatt ($\sim 10^{12}$) laser system having a central wavelength of 800 nm, a pulse duration of $\sim$ 45 fs , and a repetition rate of 1 kHz. A set of parallel plates accelerated the ions into a flight tube where they were reflected onto an MCP detector. This unique reflectron allows not only for the high precision ($\frac{m}{\Delta m} > 1000$ for Xe^+ and its isotopes) needed for efficient isotope measurements but also for obtaining intensity-resolved spectra. Our initial results for the nine stable isotopes of Xe^{q+} (q=1,2,3,4) are depicted below. By using a micrometer-sized slit and by carefully detuning our ion mirror, a one-to-one mapping between space and time-of-flight can be achieved allowing for the collection of ions from a region of space having nearly constant laser intensity [1]. As shown below (inset), the central dip in the isotopes of the lower charge state Xe^+ indicates the presence of higher-order processes such as the production of multiply charged ions, which is consistent with a sequential ionization picture. We plan to process air samples and analyze them for radioactive ^{133}Xe and ^{135}Xe tracers produced by neutron irradiation of fissionable materials within a nuclear reactor. For improved ion detection, future work will involve cryogenic xenon enriching, the use of a pulsed gas valve, and a multi kilohertz laser system.

This work was partially supported by the Robert A. Welch Foundation (grant No. A1546), the National Science Foundation (grants Nos. 0722800 and 0555568), the Air Force Office of Scientific Research (grant FA9550-07-1-0069) and Qatar National Research Fund (grant NPRP30-6-7-35).



[1].

[1]J. Strohaber and C. J. G. J. Uiterwaal, Phys. Rev. Lett. 100, 023002 (2008).

Modulation transfer spectroscopy for accurate and wideband laser locking

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Diode laser locking systems are ubiquitous in atomic physics laboratories. Modulation transfer spectroscopy (MTS) is a well-understood scheme for generating a laser frequency error signal from an atomic vapour reference. MTS offers wideband, drift-free locking with no Doppler background, and an unambiguous lock to the closed transitions needed for atomic state manipulation. Despite this, MTS is seldom used in atomic physics laboratories, perhaps because previous designs required resonant electro-optic modulation. We present a novel spectrometer layout using inexpensive acousto-optic modulators (AOMs) which allows for control bandwidths in excess of 1 MHz.

In modulation transfer spectroscopy, four-wave mixing occurs in an atomic vapour between sidebands of a frequency modulated pump laser and the probe laser. The resulting amplitude modulation of the probe is demodulated to give a dispersive error signal. The four-wave mixing process is efficient only on closed transitions, providing a distinctively simple locking spectrum (Fig. 1).

We show that a conventional AOM-based optical layout widely used for laser locking can be repurposed for MTS locking simply by redesigning the electronics. Modulation frequencies of at least 3 MHz are achieved with standard AOMs. We describe the effects of modulation frequency, demodulation phase and beam intensities on the slope, amplitude and recapture range of the MTS error signal. We also present progress towards an all-digital MTS lock controller using a field-programmable gate array.[1]

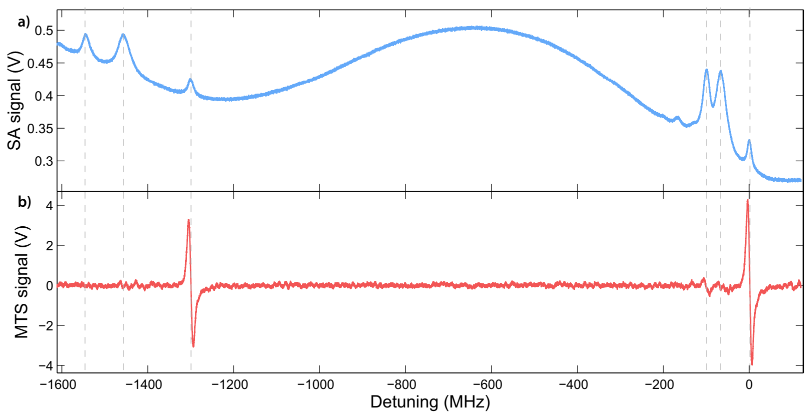

Figure 1: *Spectra of the rubidium* D_2 *transitions using* ***a)*** *saturated absorption spectroscopy and* ***b)*** *MTS. The MTS spectrum is Doppler-free and provides lock points only for the closed transitions.*

[1]Details at http://bec.physics.monash.edu.au/ModulationTransferLaserLock

Analysis of keV x-ray spectrum in laser-produced Samarium plasmas

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We have studied the characteristics of x-ray emissions in the 6.5-10$\mathring{A}$ range from the plasmas produced by the irradiation of samarium slab targets with a laser pulse of 600 ps duration at an intensity of 4×10^{13}W cm^{-2}. The prominent lines of Ni-, Co-, Fe-, and Mn-like Sm ions arising from 4f-3d radiative transition are identified. The analysis of the keV spectra indicates that the plasmas depart from pure local thermal equilibrium (LTE) regime. A collisional-radiative model has been constructed to simulate this spectrum. The intensity ratio of the resolved Ni-like Sm lines is shown to be a useful tool for electron density diagnosis.[1, 2]

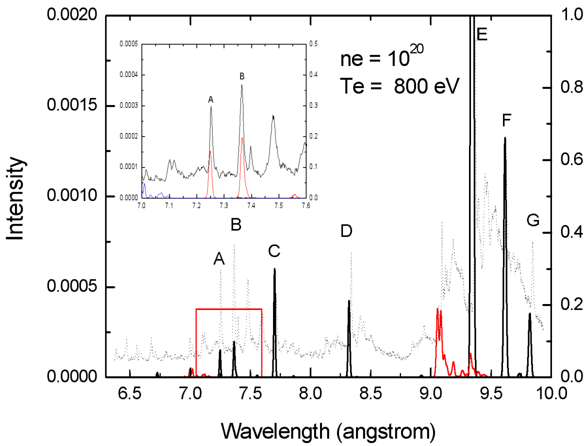

Figure 1: *Modification of the calculated Sm spectrum by multiplying the Co-, Fe- and Mn-like lines by factors of 0.269, 0.034 and 0.005 separately to fit the experimental ratio of the 4f-3d transitions from different ionization stages. Labels by alphabet correspond to the transition identification in Table 1. Dashed lines are experimental results and solid lines are theoretical results.*

[1]Electronic address: jyzhong@bao.ac.cn
[2]The author gratefully acknowledges the support of K. C. Wong Education Foundation, Hong Kong

A femtosecond frequency comb for application in a dual species atom interferometer to test the Universality of Free Fall.

A. Resch, S. Herrmann for the QUANTUS team

ZARM - Center of Applied Space Technology and Microgravity, Universität Bremen, Am Fallturm 1, 28359 Bremen

We use a compact fiber-based femtosecond frequency comb in the zero-gravity environment of the Bremen drop tower to evaluate concepts for its application in a freely falling dual species atom interferometer aiming to test the Universality of Free Fall (UFF). A drop tower compatible apparatus which is currently prepared by the QUANTUS collaboration will provide an ultra-cold mixture of Rb and K atoms as the source for such a dual species atom interferometer. The two interferometers shall be operated as a differential accelerometer where the extended time of free fall accessible in the drop tower (up to 9 s when operated in catapult mode) should allow for significantly increased resolution per shot. The frequency comb will then be used to provide a phase-link between the Raman lasers of the two atom interferometers at 780 nm and 767 nm respectively, to enable a precision measurement of the differential phase and thus the differential acceleration. The frequency comb is based on a femtosecond fiber laser and was designed by Menlo Systems specifically for the use in a drop tower experiment.
Such an experiment in the drop tower is intended to serve as a pathfinder for a future space based implementation e.g. on the International Space Station, where the full potential of matter wave interferometry with extended free evolution time and integration over a large number of measurements might be realized.
We will present the underlying concepts for the application of the comb in a test of the UFF and report on the current status of the drop tower experiment.
We acknowledge support by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50 WM 0842.

Production of Ba meta-stable states via super-radiance

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[2]*Kyoto University, Kyoto 606-8502, Japan*

Recently some of the authors have found that coherent volume of super-radiance, a class of cooperative coherent optical phenomenon predicted by Dicke in 1954 and confirmed by subsequent experiments, [1] can be made free from its wavelength restriction if a process under consideration emits plural particles or radiations.[2] In fact, the coherent volume can be macroscopic when outgoing particles satisfy a certain phase matching condition. Our ultimate goal is use of this mechanism, named as ”macro-coherent amplification mechanism”, for investigating natures of neutrinos, for example, their absolute mass scale, and mass type of Dirac or Majorana. [3]

We present some preliminary results of an experiment which is intended to prove the principle of the macro-coherent amplification mechanism. We like to do it with a process which emits two photons from atomic states excited coherently (paired super-radiance): observation of back-to-back radiations with almost equal energy is an unambiguous proof of the principle. One important step of the experiment is to produce meta-stable states, the initial atomic states from which paired super-radiance is supposed to occur. The state we are of interests is Barium meta-stable states ($6s5d$, $^1D_2$); their radiative life time to the ground states ($6s^2, ^1S_0$) is ∼1/8 sec. We obtain them via super-radiance from intermediate states ($6s6p$, $^1P_1$).

In the actual experiment, we injected 554nm laser lights to excite Ba atoms to $^1P_1$. One salient feature of our method was use of a trigger laser; 1500nm CW laser lights corresponding to $^1P_1 - ^1D_2$ energy difference was injected to accelerate the transition. Fig.1 shows the results; the angular dependence of 1500nm super-radiance intensity observed by a photo-diode detector without (a) and with (b) the trigger laser. Introduction of trigger laser not only speeded up the transition from $^1P_1$ to $^1D_2$ but also sharpened its angular divergence. We obtained the $^1D_2$ production rate of 10^{13} atoms in a few nano seconds. The results of the experiment will be reported in detail.

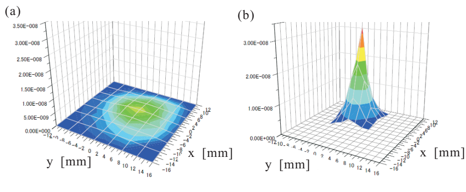

Figure 1: *Angular distribution of super-radiance without (a) and with (b) trigger laser.*

[1]R.H. Dicke, Phys. Rev. 93, 99 (1954), see also M. Benedict *et.al.*, Super-radiance (Informa, 1996)
[2]M.Yoshimura *et.al.*, arXiv:0805.1970v1 [hep-ph] 14 May 2008
[3]M.Yoshimura, Phys. Rev. D 75, 113007 (2007); M.Yoshimura *et.al.*, Prog. Theo. Phys. 123, 523 (2010)

Towards a Quantum Test of the Equivalence Principle Using Atom Interferometry

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[1]*Institute of Quantum Optics, Leibniz Universitt Hannover, Welfengarten 1, 30167 Hannover, Germany*
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We present our experimental approach to a dual species atom interferometer performing a differential acceleration measurement with quantum objects, namely ^{87}Rb and ^{39}K atoms, to test the weak equivalence principle (Universality of Free Fall, UFF).

A compact and versatile laser system provides 5 W for incoherent and coherent manipulation of both species allowing for trapping, cooling and driving stimulated Raman transitions with the same laser setup. Atoms are loaded into a three dimensional magneto-optical trap (3D-MOT) using a 2D-MOT. The system provides an optical dipole trap at a wavelength of 1.96 μm to enable very accurate initial position control of the two ensembles and leaves options for evaporative and sympathetic cooling and the use of quantum degenerate gases in the differential interferometer. After dropping the atoms from the dipole trap a Mach-Zehnder interferometry sequence will be performed for both species simultaneously . A detection cube below the trapping region allows for high NA state selective fluorescence detection.

Progress on the measurement of the francium anapole moment

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[1]*Joint Quantum Institute, Department of Physics, University of Maryland and National Institute of Standards and Technology, College Park, MD, USA*

We present the current status of the experimental effort towards the measurement of the anapole moment in francium. The anapole moment is a parity violating, time-reversal conserving nuclear moment that arises from the weak interaction among nucleons. It is nuclear spin dependent (nsd) and sensitive to the configuration of nuclear structure. Our experimental scheme is to perform a direct measurement of the nsd parity violation, by driving a parity forbidden E1 transition between hyperfine ground states in a series of francium isotopes inside a blue detuned dipole trap at the electric anti-node of a microwave cavity. We explore on the possible tests using rubidium isotopes. The progress includes the design of a Fabry-Perot microwave cavity, the test of phase controlled interference between interactions and applications of the blue detuned dipole trap on the study of classical atom trajectories. The francium experiment will be at the ISAC radioactive beam facility of TRIUMF, Canada. Work supported by NSF and DOE, USA.

Symmetry Consequences of Special Relativity in an Expanding Hyperbolic Cosmology

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Special relativity (SR) can be extended to the hyperbolic geometry of the simplest useful model of the Hubble expanding universe. Both position and velocity space then have negative curvature and each separately supports its own Lorentz subgroup $\mathrm{L_{posn}}$ and $\mathrm{L_{vel}}$. These combine in a direct product group, the double Lorentz group $\mathrm{L}^2 = \mathrm{L_{posn}} \otimes \mathrm{L_{vel}}$. Cosmic time t_{cosm} is orthogonal to the hyperbolic variables of both the velocity and position spaces, and has its own one-parameter translational subgroup. This combines with the 12-parameter group L^2 to form the 13-parameter hyperbolic Poincaré group $\mathrm{P_{hyp}}$. Position 3-space expands linearly in cosmic time t_{cosm}. Translational shifts are like boosts in velocity space, but expressed through an increment Δr scaled by the Hubble radius $\rho = ct_{\mathrm{cosm}}$. The operators of the direct product group must be represented by 8x8 matrices, constructed block-diagonally from the 4x4 matrices of the subgroups $\mathrm{L_{posn}}$ and $\mathrm{L_{vel}}$. The spatial curvature entails new angular momentum effects, arising because each of the two Lorentz subgroups has its own R(3) rotational subgroup. These bring in new operators permitting very weak transitions that would be totally forbidden under the zero curvature symmetry of flat Minkowski space-time in the Poincaré group. Because some of these operators appear only as 8x8 matrices, they can represent curvature effects in dynamics that will not appear at all at the level of the 4x4 tensors of special and general relativity. A coupling operator appears that depends on the product $(\mathbf{r} \times \mathbf{v})/\mathbf{c}\rho$. Since ρ, the Hubble length, is a measure of curvature length, this term is very weak and vanishes when the curvature vanishes. Its presence suggests there will be stronger effects of a similar kind in the presence of stronger local curvature features. Such terms will be expected to be important especially in regions of high curvature arising from strong gravitation fields.

High-power picosecond laser source with 300 MHz repetition rate for trapped-ion quantum logic

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[2]*Interdisciplinary Photonics Laboratories (iPL), School of Chemistry, Madsen Building F09, University of Sydney, Sydney NSW 2006, Australia*
[3]*OFS Laboratories, Somerset, New Jersey 08873, USA*

Trapped ions are a major candidate technology for scalable quantum computation. However, current methods for performing quantum logic gates with trapped ions are limited by the trap frequency. A scheme has been developed where this limitation is removed, potentially allowing for a factor of 10^3 increase in gate speed.[1] The scheme uses pairs of counterpropagating π-pulses, resonant with an allowed ion transition, which impart a large selective force that scales with repetition rate of the laser source.

We are developing a fibre-based source of picosecond pulses resonant with the 370 nm allowed transition of the Yb^+ ion. We first produce mode-locked 1108 nm light from an octave-spanning supercontinuum with fibre Bragg grating (FBG) enhancement at the desired wavelength.[2] We filter this wavelength and reamplify to 10 W of average power, which will undergo second harmonic generation (SHG). The produced 555 nm light undergoes sum frequency generation (SFG) with the remaining IR. We present work toward efficient upconversion, where simulations show a 25% upconversion efficiency of this light to 370 nm for these parameters.

We use an Er-doped fibre laser, harmonically mode-locked at a 300 MHz repetition rate, to seed the supercontinuum generation — this directly determines the output repetition rate. This technique is scalable to very high average power and repetition rate, allowing for good resonant gate performance in highly parallel logic operations.[3]

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[1]J.J. Garcia-Ripoll, P. Zoller, and J.I. Cirac, "'Speed Optimized Two-Qubit Gates with Laser Coherent Control Techniques for Ion Trap Quantum Computing," Phys. Rev. Lett. **91**, 157901 (2003)

[2]D. Kielpinski *et al.*, "Mode-locked picosecond pulse generation from an octave-spanning supercontinuum," Opt. Express **17**, 20833-20839 (2009)

[3]D. Hayes *et al.*, "Entanglement of Atomic Qubits Using an Optical Frequency Comb," Phys. Rev. Lett. **104**, 140501 (2010)

Spin Dependent Forces on Trapped Ions: Entangled Matter Wave Dynamics and Decoherence

U.G. Poschinger[1,2], A. Walther[1,2], F. Ziesel[1,2], M. Hettrich[1,2], K. Singer[1,2], F. Schmidt-Kaler[1,2]

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We aim at the experimental realization of scalable quantum information with qubits encoded in the electron spin of $^{40}Ca^{+}$ ions in a segmented microchip ion trap. The qubit manipulation for single- and two qubit gates are realized by stimulated Raman transitions driven by off-resonant laser fields [1]. We present a detailed study of the quantum dynamics of a single trapped ion exposed to laser fields which resonantly drive its motion along the trap axis. The precise investigation of the ions dynamics is a fundamental importance for the realization of fast and accurate two-ion gates, and a cornerstone for the application of advanced quantum control techniques. We show complementary approaches for the readout of the motional state: i) by monitoring the ions spin coherence, ii) by reconstructing the quantum state of the motional degree of freedom by mapping out phonon number distribution and iii) by measuring the ions trajectory in phase space with a wavepacket homodyne measurement. We show that with the latter method, a simultaneous statistical measurement of position and momentum with an accuracy below the Heisenberg limit is possible. As a result, we measure deviations from the dynamics predicted by the Lamb-Dicke approximation [2]. Furthermore, we present a detailed study of the relevant decoherence processes. These include on the one hand spontaneous photon scattering, for which we have measured the effect of the scattering of the motional state of the ion. On the other hand, we have investigated the effect of the initial ion temperature on the dynamics of spin and motion, allowing precise estimates of the requirements for scalable quantum information in microstructured ion traps.

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Generation of entangled states of two ions using adiabatic passage

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Multipartite entanglement plays a central role in quantum information science. In various systems, including photons and trapped ions, entangled states are generated and studied, while with increased numbers of particles it becomes difficult to generate and analyze such states.

For a string of ions, a relatively simple and effective method for generation of an important class of entangled states called symmetric Dicke states is proposed by Linington et al.[1], which requires at minimum only two chirped pulses for adiabatic passage. Symmetric Dicke states are defined as $|D_N^{(m)}\rangle \equiv ({}_NC_m)^{-1/2}\sum_k P_k(|\downarrow^{\otimes(N-m)}\uparrow^{\otimes m}\rangle)$ (the sum is over all ${}_NC_m$ permutations denoted as P_k), which is known to be robust against partial measurement or loss of particles. The method in [1] is applicable to $|D_N^{(m)}\rangle$ with arbitrary N and m. For smaller numbers of excitation m, non-chirped pulses can also be used to produce $|D_N^{(m)}\rangle$, although in this case perfect fidelity is possible only when $m = 1$. Hume et al. [2] analyzed attainable fidelities with the method using non-chirped pulses and experimentally demonstrated it using two $^{25}Mg^+$ ions. Sufficiently high fidelities are estimated in [2] for $m = 2, 3$ with non-chirped pulses, while use of adiabatic passage may make the generation process insensitive to such imperfections as intensity fluctuation or frequency drift of lasers.

We have generated an entangled state of two ions, $|D_2^{(1)}\rangle$, by using adiabatic passage on the $S_{1/2}$–$D_{5/2}$ transition of $^{40}Ca^+$. Fig. 1 shows a parity oscillation with frequency 2 when additional two $\pi/2$ analysis pulses are applied with the phase of the second varied. From this and population measurements, we infer that $|D_2^{(1)}\rangle$ is generated with fidelity exceeding 0.6. Details including fidelity analysis will be given in the session.

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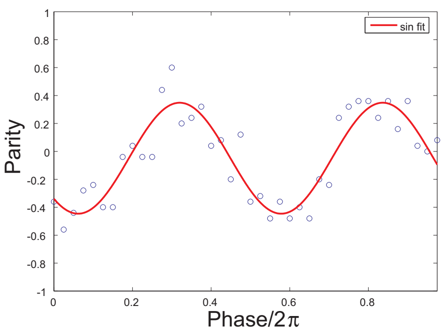

Figure 1: *Parity oscillation after two $\pi/2$ analysis pulses.*

Superconducting microfabricated ion traps for studies of anomalous heating in trapped ions

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Dense arrays of ions in microfabricated traps are a promising possibility for scaling up ion trap quantum information processing. However, heating rates far exceeding Johnson noise limits severely affects the motional state coherence at small trap sizes. Current evidence shows that by cooling to cryogenic temperatures, the anomalous heating is reduced by orders of magnitude from room temperature values, though still above the thermal limit[1,2]. This invites the possibility of distinguishing candidate noise models by comparing traps made of normal metals and of superconductors. For example, charge noise from bulk sources should be suppressed in superconducting traps. We fabricate superconducting ion traps with niobium and niobium nitride and trapped single ^{88}Sr ions at cryogenic temperatures. The lowest observed heating rate is comparable to that in gold and silver traps, suggesting that anomalous heating is primarily caused by surface, not bulk, effects. Heating rates above and below the superconducting transition are compared to further investigate the effect of charge fluctuations on ion heating. Nevertheless, we show that anomalous heating need not be a limiting factor in gate fidelity and that microfabricated traps are compatible with quantum operations, by performing a controlled-NOT gate using a single ion's atomic and motional states[3]. This demonstration of superconducting ion traps opens up possibilities for integrating trapped ions and molecular ions with superconducting devices, such as photon counting detectors, microwave resonators, and circuit-QED systems[4].

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