POSTER ABSTRACTS

The *p*-orbital Bose-Einstein condensation of two-species mixture in a bipartite square optical lattice

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In recent years, the unconventional Bose-Einstein condensation (BEC) in the *p*-orbital band of an optical lattice, has been under active studies both theoretically and experimentally [1-4]. In this presentation, we investigate the *p*-orbital BEC of two-species mixture in a bipartite optical lattice by solving Gross-Pitaevskii equation numerically. We have developed a reliable imaginary-time propagation method applicable to a truncated basis where the ground state is excluded, to locate the lowest-energy states in the *p*-orbital band. We find that the *p*-orbital BEC states depend crucially on the ratio of g_{AB}/g_{AA}, where $g_{AB}>0$ is the inter-species interaction and $g_{AA}=g_{BB}>0$ are the intra-species interactions. When $g_{AB}/g_{AA}<1$, each species is characterized independently by one of the two degenerate, time-reversal-symmetry-broken and staggered orbital-current orders, $p_x \pm ip_y$. Conversely, when $g_{AB}/g_{AA}>1$, the two species are characterized respectively by the two mutually orthogonal and time-reversal-symmetry-preserved orders, p_x+p_y and p_x-p_y, or vice versa.

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Dynamics of ultracold atoms in amplitude-modulated parabolic lattices

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Ultracold atoms in amplitude modulated optical lattices is a promising tool for generation of matter wavepackets for interferometry [1], and for fulfilling quantum simulations of complicated solid-state phenomena [2]. Here we extend a semiclassical theory developed by one of us (A.I.) for the Hamburg experiment with ultracold fermions [2]. We firstly consider a particle in a combined optical lattice and parabolic trap potential in 1-dimension, and predict the form of the wavepacket in an excited band of the lattice after an amplitude modulation pulse. In the bosonic system [1], it allows us to achieve more efficient population transfer. We also apply it to the system of noninteracting fermions [2] and analyze the detailed structure of the wavepacket. This allows, in particular, to predict subsequent dynamics of the system on longer times.

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Bose Gases Mo-003

Novel quantum phenomena of atomic quantum gas in a shaken optical lattice

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Ultracold atoms in optical lattices have proven to be clean, controllable systems for exploring a variety of strongly correlated many-body phenomena. We have developed the capability to hybridize targeted Bloch bands by resonantly shaking the optical lattice potential [1]. When the shaking amplitude reaches a threshold value, a Bose condensate can acquire an asymmetric dispersion relation with a minimum at a finite quasi-momentum (similar to roton dispersion in He-4). To probe the dispersion, we employ a digital micromirror device to imprint an optical excitation with controllable wavelength and energy. From time of flight and in situ images, we plan to map out the full dispersion relation and identify the minimum. Finally, we will also attempt to drag an optical barrier through the cloud and directly measure the critical velocity. Our study would demonstrate the power of shaken optical lattices to explore new classes of quantum phenomena in condensed matter materials with exotic band structure.

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Direct observation of chiral order in double layer superfluid

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A double layer chiral superfluid is formed in the second band of a bipartite optical square lattice. In an ballistic expansion process the two layers are superimposed. The Bragg maxima thus observed exhibit interference patterns, which provide direct information on the formation of chiral order and the presence and character of low energy excitations. Furthemore we report on the progress of setting up a new bose-fermi mixture experiment.

MONDAY

Effective preparation of atomic condensates in excited bands of an optical lattice by standing-wave pulses

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We present a method for the effective preparation of a Bose-Einstein condensate (BEC) into the excited bands of an optical lattice via a standing-wave pulse sequence. With our method, the BEC can be prepared in either a single Bloch state in an excited band or a coherent superposition of states in different bands. Our scheme is experimentally demonstrated by preparing a BEC into the *d* band and the superposition of *s*- and *d*-band states of a one-dimensional optical lattice, within a few tens of microseconds. We also measure the decay of the BEC in the *d*-band state and carry an analytical calculation for the collisional decay of atoms in the excited-band states. Our theoretical and experimental results agree well [1]. Furthermore, the diffraction phases of different orders are studied for ultracold atomic gases scattered by a standing-wave pulse [2].

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Tunneling-Induced Restoration of the Degeneracy and the Time-Reversal Symmetry Breaking in Optical Lattices

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The ground-state properties of bosons loaded into the p-band of a one dimensional optical lattice is studied. It is shown that the phase diagram of the system is substantially affected by the anharmonicity of the lattice potential. In particular, for a certain range of tunneling strength, the full many-body ground state of the system becomes degenerate. In this region, an additional symmetry of the system, namely the parity of the occupation number of the chosen orbital, is spontaneously broken. The state with nonvanishing staggered angular momentum, which breaks the time-reversal symmetry, becomes the true ground state of the system.

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Using Tilted, Modulated Lattices to Implement Novel Hamiltonians

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We first present our implementation of the Harper Hamiltonian in neutral atoms using the general tools of a tilted lattice with laser-assisted tunneling in one direction [1]. We have demonstrated control over the amplitude of the laser-assisted tunneling, but have not yet achieved the ground state and so have not seen the phase structure associated with Hofstadter's butterfly. Our scheme can be extended to realize spin-orbit coupling and the quantum spin Hall effect [2]. We report on further studies of a simpler system: a tilted lattice with amplitude modulation. We demonstrate restoration of coherence and a lifetime of over a thousand cycles. We explore the effect of the dimensionality of the lattice, interaction strength, modulation strength, and tilt depth on dephasing due to the dynamic instability and micromotion. We present a region of stability, which provides a starting point for the many proposals for quantum simulation using tilted lattices.

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MONDAY

Bosons in optical lattices: beyond the Bose-Hubbard Hamiltonian

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The standard approximation to describe a set of bosonic neutral atoms loaded in optical lattices is the discrete Bose-Hubbard (BH) Hamiltonian. In fact, the first examples of those systems were hailed as experimental realizations of that approximate model. However, we found that the set of simplifications involved in the derivation of the BH model make it unsuitable to describe many real optical lattices. We present here zero-temperature phase diagrams for the complete (non discrete) continuous Hamiltonians that model those arrangements. That allowed us to check the validity of the Bose-Hubbard approximation for quasi-one dimensional systems (''tubes'') and asymmetric ($V_x=V_y \neq V_z$) ones. In particular, we concluded that for very thin ''tubes'' and asymmetric three-dimensional lattices, the BH prescription differs significantly from our results. Our data can serve as a reference to future experiments in the field, since we explore parts of the phase diagram that are not well modeled by the BH Hamiltonian.

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Ultracold Atoms in a Tunable Optical Kagome Lattice

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We realize the Bose-Hubbard model on a triangular lattice with a tunable basis by loading ultracold ^{87}Rb into commensurate 532 nm and 1064 nm triangular lattices. Each lattice is actively stabilized on a common path, preserving the phase relationship. We detail recent improvements to this scheme that allow dynamic in-loop control of the lattice geometry and shifting of the lattice over many periods.

This control over the lattices allows us to realize the Kagome lattice, and explore methods to populate its dispersionless third band. We investigate phase modulation of the lattice to invert the band structure, and we explore dynamic shifting of the two lattices to populate higher bands. We also explore next-nearest neighbor tunneling in an inverted triangular lattice.

Bose-Einstein condensation of ultra-cold atoms in a frustrated, triangular optical lattice

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We present a study of Bose-Einstein condensation of ultracold atoms in a triangular optical lattice. As demonstrated in Ref. [1], the tunneling energy between neighboring sites in an optical lattice can be controlled via lattice shaking to be negative or complex-valued. For negative, real-valued tunneling, the system condenses at one of two non-zero quasimomenta, corresponding to classical frustration. Tuning the tunneling energy to complex values corresponds to an artificial gauge field. We demonstrate that the nature of the condensation transition is modified due an additional symmetry that is broken, a chiral symmetry. Furthermore, the artificial gauge field acts as the conjugate external field to the chiral order parameter, which allows to map out magnetization curves of the chirality as a function of the article gauge field. We give analytical results on the nature of the phase transition, based on an expansion of the free energy in the interaction strength and on a renormalization group approach, and numerical ones, based on Monte Carlo simulations.

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Magnetometric Probe of an Ultra-cold Spinor Gas

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Ultracold atoms have been shown to permit highly sensitive micron-scale magnetometric measure- ments. Here, we propose that a cold-atom magnetometer offers a new and sensitive method of probing the magnetic state of a second nearby ultracold spinor gas. We analyze the measurement back-action from such a magnetometric probe for polar-state and ferromagnetic-state probes, and compare to a Heisenberg-limited measurement.

Quantum dynamics of spin waves using ultracold atoms

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Ultracold-atom experiments are suitable to study out-of-equilibrium dynamics of quantum many-body systems. Here we will report the quantum dynamics of deterministically created mobile spin impurities as well as spin spirals in the bosonic atoms in optical lattices. First, we investigate the dynamics of a single-spin impurity in a one-dimensional spin chain [1]. Coherent propagation of the single spin, which generates and transfers entanglement, is observed. Second, we examine bound states of two magnons in a Heisenberg chain by tracking their dynamics. Such bound states were theoretically pointed out by H. Bethe in 1931, and our novel microscopic study of quantum magnets can directly confirm their existence [2]. Third, we study the decay of highly excited states of spin spirals and discuss their diffusive behavior.

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Quantum control of a many-body system in a spin-1 Bose-Einstein condensate

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Spin-1 condensates provide a useful platform for investigations of quantum control. By tuning the relative strength of the Zeeman and spin interaction energies, the spin dynamics behave similarly to a quantum pendulum. In the inverted pendulum case, the condensate is initialized to an unstable (hyperbolic) fixed point, and we demonstrate the dynamic stabilization by periodic manipulation the phase of the quantum states. In the case of a simple quantum pendulum, the condensate is initialized to an (elliptical) energy contour and we demonstrate the parametric excitation by modulating the relative strength of the Zeeman and spin interaction energies.

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MONDAY

Investigation of Kibble-Zurek quench dynamics in a spin-1 ferromagnetic BEC

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We study the temporal evolution of spin populations in small spin-1 Rb-87 condensates following a slow quench. A ferromagnetic spin-1 BEC exhibits a second-order gapless (quantum) phase transition due to a competition between the magnetic and collisional spin interaction energies. The dynamics of slow quenches through the critical point are predicted to exhibit universal power-law scaling as a function of quench speed. In spatially extended condensates, these excitations are revealed as spatial spin domains. In small condensates, the excitations are manifest in the temporal evolution of the spin populations illustrating a Kibble-Zurek type scaling [1]. We will present the results of our investigation and compare them to full quantum simulations of the system.

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Metastable Spin Texture of Spin-1 Bose-Einstein Condensates in a Ring Trap

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Various properties of superfluidity, such as persistent current, and hysteresis, were investigated by recent experiments of Bose-Einstein condensates trapped in a ring geometry[1,2,3]. Motivated by these experiments, we investigate properties of spin-1 Bose-Einstein Condensates(BECs) in a quasi-one-dimensional rotating ring by solving the Gross-Pitaevskii(GP) and the Bogoliubov equation. We find analytical solutions of metastable energy branches, which exhibit spin textures. These solutions correspond to one-dimensional version of the polar-core vortex. We also find that the number of type-I and type-II Nambu-Goldstone(NG) modes changes at a certain rotation velocity(type-I-type-II transition[4]). The physical origin of the change of the number of the NG modes will be discussed.

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MONDAY

Dipolar ultracold atoms in a double well trap

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We have investigated the physics of spin exchange processes with a chromium dipolar BEC loaded in a double well trap. We can prepare one cloud in one well in the lowest energy Zeeman state (ms=-3), and the other one in the other well in the highest energy Zeeman state (ms=+3).

We show that dipolar spin exchange processes between these two separated large ensembles of atoms are prohibited, in stark contrast with our previous results obtained in 3D optical lattices [1]. We interpret our results due to the classical behaviour of a large ensemble of spins.

When we merge the two wells, spin exchange dynamics due to contact interactions occur. Analysis of the dynamics provides the first measurement of one scattering length of ^{52}Cr, a_0. The value we find (-100 a_B) shows that the low B field ground state of the spinor ^{52}Cr BEC is polar [2,3].

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Quantum phases in an asymmetric double-well optical lattice

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We study the superfluid (SF) and Mott insulator phases of ultracold atoms trapped in a double-well optical lattice. The lattice has an asymmetric double-well geometry along the x axis and single wells along the other axes. We evaluate the tunneling and atom-atom interaction energies from exact band-structure calculations. We then show that a comparable tight binding (TB) model should include all tunneling terms between two neighboring double-wells, i.e, a total of six different hopping terms. In addition, there is tunneling $J_{\perp}$ along the other directions. We set up the appropriate Bose-Hubbard Hamiltonian, and a mean field calculation determines the SF and Mott phase boundaries as a function of lattice parameters and chemical potential μ. The boundary is largely characterized by an effective tunneling $t_{\rm eff}=t+J$ along the x axis. Moreover, for $t_{\rm eff}\ge 4J_{\perp}$, we always have a SF phase. In future, we will use the results of these simulations to construct effective lattice models where the atom-atom interaction is zero and the interactions are governed by a three-body potential. Such systems might lead to unique many-body ground states.

Experiments with BECs in a Painted Potential: Atom SQUID, Matter Wave Bessel Beams, and Matter Wave Circuits

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The Painted Potential is a time-averaged optical dipole potential which is able to create arbitrary and dynamic two dimensional potentials for Bose Einstein condensates (BECs). This poster reports three recent experiments using this technique. First, we have realized the dc atom SQUID geometry of a BEC in a toroidal trap with two Josephson junctions. We observe Josephson effects, measure the critical current of the junctions, and find dynamic behavior that is in good agreement with the simple Josephson equations for a tunnel junction with the ideal sinusoidal current-phase relation expected for the parameters of the experiment. Second, we have used free expansion of a rotating toroidal BEC to create matter wave Bessel beams, which are of interest because perfect Bessel beams (plane wave with amplitude profiles described by Bessel functions) propagate without diffraction. Third, we have realized the basic circuit elements necessary to create complex matter wave circuits. We launch BECs at arbitrary velocity along straight waveguides, propagate them around curved waveguides and stadium-shaped waveguide traps, and split them coherently at y-junctions that can also act as switches.

Observation of Solitonic Vortices in Bose-Einstein Condensates

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We observe solitonic vortices in an atomic Bose-Einstein condensate after free expansion. Clear signatures of the nature of such defects are the twisted planar density depletion around the vortex line, observed in absorption images, and the double dislocation in the interference pattern obtained through homodyne techniques. Both methods allow us to determine the sign of the quantized circulation. Experimental observations agree with numerical simulations. These solitonic vortices are likely the decay product of grey solitons spontaneously created after a rapid quench across the BEC transition in a cigar-shaped harmonic trap via the Kibble-Zurek mechanism and are shown to have a very long lifetime.

Ring Dark Solitons in Toroidal Bose-Einstein Condensates

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Ring dark solitons (RDSs) are examples of nonlinear quantum states that can be supported by a Bose-Einstein condensate (BEC). Unlike the well-known planar dark solitons, exact analytic expressions for RDSs are not known. We address this problem by presenting exact localised soliton-like solutions to the radial Gross-Pitaevskii equation. To date, RDSs have not been experimentally observed in cold atomic gases, either. To this end, we propose two protocols for their creation in experiments. In addition, we present results regarding the dynamics and stability of RDSs. Under certain trapping potentials, we show that the decay of RDSs into circular arrays of vortex-antivortex pairs can be reversible, but eventually the decay leads to a state with some properties of quantum turbulence.

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Bose Gases Mo-021

One dimensional atomic rings with barriers: a Luttinger liquid approach to precision measurement

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Recent experiments [1] have realized ring shaped traps for ultracold atoms which can be 'stirred' with a moving laser. Here, a similar 1D ring system is imagined and analyzed using the framework of Luttinger liquid theory. Using the duality in Luttinger theory, we simultaneously consider systems of superfluid atoms with a weak link and long-range repulsive atoms (or ions) with a weak barrier. We find that classical theory suggests high precision sensors can be constructed from these systems; we attempt to extend these results into the quantum regime.

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Finite-Temperature Effects in ring-shaped Bose-Einstein condensates

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A recent experiment performed at NIST [1], in which hysteretic behavior of a stirred, ring-shaped Bose-Einstein condensate (BEC) was demonstrated, has shown quantitative disagreement with zero-temperature mean-field theory. We have studied finite-temperature effects in this system by applying the Zaremba-Nikuni-Griffin (ZNG) theory to model the experiment. The ZNG theory describes the system as consisting of both a condensate and a non-condensate. It allows for time-dependent evolution of both parts and for them to interact and exchange particles. The evolution of the condensate is described by a dissapative generalized Gross-Pitaevskii equation while the non-condensate evolution is governed by a quantum Boltzmann equation. We show how the presence of a thermal cloud modifies the behavior of vortices produced during the stirring process compared to their behavior at zero temperature.

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Investigation of Critical correlations in an ultracold Bose gas by means of a temporal Talbot-Lau interferometery

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Phase transitions is a popular phenomena in nature, among them the transition from normal fluid to superfluid for helium is a famous one. Rubidium gas, while the temperature of it is reduced to the nano kelvin region, will alter from the normal gas to the quantum gas, the Bose-Einstein condensate, which is the phase of superfluidy. The phase transition takes at the critical point. Similar to the helium, the correlation length will grow to infinity as the critical point is approached, In this presentation we report that we develop a method, temporal Talbot-Lau (TL) interferometer, to measure this lamda transition point for rubidium gas at the temperature as low as 50 nano kelvin. This approach demonstrates the potential application of the Talbot–Lau interferometer to a wide range of critical phase transitions in ultra-cold atomic gases [1] and atomic interferometer in high sensitivity [2].

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Collective modes of a two-dimensional quantum gas

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The study of the excitation modes of a quantum gas is a way to characterize its dynamical properties. The low energy excitations of a quantum gas trapped in an harmonic potential are collective modes. They can be excited by inducing a sudden change in the trap parameters. Here, we present results of the study of two important collective modes of a two-dimensional bosonic quantum gas [1]: the monopole mode (or breathing mode), and the scissors mode. In particular, we show that the third, strongly confining dimension has a measurable effect on the breathing mode frequency, in agreement with our theoretical predictions and numerical simulations [2]. The scissors mode can be used to characterize the superfluid phase. We study its frequency and damping as a function of temperature across the transition to degeneracy.

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Measurement-based control of many-body systems

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Quantum control is an ambitious framework for steering dynamics from initial states to arbitrary desired final states. While immensely successful in low dimensions, it has been applied only to a limited extent to many-body systems such as atoms in optical lattices. Most generic quantum control schemes require either a controllable system Hamiltonian or a large set of measurement operators.

We have developed a new minimalistic control scheme based on a combination of fixed unitary evolution and repeated quantum non-demolition (QND) measurements [1].

As an initial step towards a realization we present our experimental results on the continuous, highly resolved QND probing of the quantum phase transition between a thermal cloud and a BEC. The continuous probing enables instantaneous feedback control of the system as well as very efficient single-shot detection of entire phase diagrams - a technique also applicable to the superfluid to Mott insulator transition in optical lattices [2].

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A novel experiment for coupling a Bose-Einstein condensate with two crossed cavity modes

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Over the last decade, combining cavity quantum electrodynamics and quantum gases allowed to explore the coupling of quantized light fields to coherent matter waves, leading e.g. to new optomechanical phenomena and the realization of quantum phase transitions. Triggered by the interest to study setups with more complex cavity geometries, we built a novel, highly flexible experimental system for coupling a Bose-Einstein condensate (BEC) with optical cavities, which allows to switch the cavity setups by means of an interchangeable science platform. The BEC is produced from a cloud of laser-cooled ^{87}Rb atoms which is first loaded into a hybrid trap, formed by a combined magnetic and optical potential. We use an optical setup involving focus-tunable lenses to optically transport the atomic cloud into the cavity setup, where it is cooled down to quantum degeneracy.

At first we aim to explore the coupling of a BEC with two crossed cavity modes. We report on our progress on the implementation of a science setup involving two cavities intersecting under an angle of 60°. The mirrors have been fabricated in order to spatially approach them, thus obtaining maximum single atom coupling rates of several MHz. This setup will allow us to study the coherent interaction of a BEC and the two cavity modes both in internal lambda-level transitions and in spatial self-organization processes in dynamical hexagonal lattices.

Heat Capacity of a Bose-Einstein condensate measured through Global variables

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We have developed a new technique which allows for the determination of the global heat capacity of Bose-Einstein condensates [1,2], across the phase transition. A pair of global conjugate variables is defined then we determine the system's total internal energy and its temperature derivative, the heat capacity. A rapidly changing C_V was observed in the vicinity of the critical temperature, in a ^{87}Rb BEC, very similar to the λ point in liquid ^{4}He.

The evolution of the measured C_V , near the critical temperature, suggests an interplay of the mean field interactions. The more interesting observed effects are: the T_c absolute value downshift; the C_V peak round off; and, the larger values of the normalized C_V for lower N in a relatively broad T range, below the critical temperature.

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Probing the excitation spectrum of a ring-shaped Bose-Einstein Condensate

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Bose-Einstein condensates confined in ring geometries provide us with a powerful tool to study bulk superfluidity in finite systems. Recently, the NIST experiment demonstrated the controlled introduction of quantized superfluid currents using a blue-detuned Gaussian beam as a potential barrier [1]. Here, we model an experiment where this barrier is used to selectively excite collective excitations in a ring-shaped condensate. We present full calculations of the collective excitation spectrum, and use time-dependent simulations of the Gross-Pitaevskii equation to model the proposed experimental protocol. We demonstrate that the appropriate stirring of the barrier can resonantly excite selective modes, which in turn depletes the condensate and excites atoms out of the trap, providing a clear experimental signature of the spectrum

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Dynamics of coupled mixtures in optical lattices

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Bosonic quantum-gas mixtures in optical lattices allow for a wide range of studies including disordered systems, dissipative phenomena, and out-of-equilibrium effects. We subject a bosonic rubidium gas to species-selective optical lattice potentials and drive coherently between two hyperfine ground states. We observe non-trivial coherent oscillations between the localized atoms and superfluid. Results of further experiments on the interplay between coupling strength and interactions in the mixture will be discussed.

Superfluid Atomtronic Circuits

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We have created a superfluid atom circuit using a toroidal Bose-Einstein Condensate. Just as a current in a superconducting circuit will flow forever, if a current is created in our superfluid circuit, the flow will not decay as long as the current is below a critical value. A repulsive optical barrier across one side of the torus creates a tunable weak link in the condensate circuit and can be used to control the current around the loop. By rotating the weak link, we have observed phase slips between well-defined persistent current states, which are analogous to transitions between flux states in an rf-superconducting quantum interference device (SQUID). Importantly, we have demonstrated that these transitions are hysteretic, a characteristic of many common electronic circuits like memory, digital noise filters, and, indeed, the rf-SQUID. More recently, we have realized a geometry similar to a dc-SQUID using two weak links. In this case, we can move these weak links relative to each other and observe resistive flow when the current exceeds the critical current. This observation of resistive flow is an important step to realizing the atomtronic analog of the dc-SQUID. Lastly, we have developed techniques of measuring the current flow around the ring which allows us to measure the current-phase relationship of our weak link.

Emergence of coherence in a 2D uniform Bose gas

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The emergence of coherence in a 2D Uniform Bose gas is fundamentally different from both the 3D and the 2D harmonic case. First, in this case, Bose Einstein condensation is precluded in the thermodynamics limit but it can be recovered in finite size system when the correlation length becomes of the order of the size of the system itself. Second, the 2D regime can then be reach even when the spacing of transverse ground and first excited state is not greater than the thermal energy $k_B T$. The 2D nature then rely on the so-called transverse condensation phenomenon that was previously mainly described for a 1D harmonically trapped gases [1-3].

We experimentally investigate the appearance of coherence in a Bose gas trapped by a 2D flat bottom potential and a transverse harmonic one. Here, the coherence is characterized in two ways, first by the bimodality of the density distribution in time of flight measurement, second by fringes pattern appearing when interfering two identical systems.We compute the phase diagrams of these coherence parameters versus the temperature T and the number of atoms N and enhance the importance of the transverse condensation phenomenon.

Finally, we show some dynamics features of the crossing of this superfluid transition by characterizing nucleation of single vortices by Kibble Zurek like mechanism.

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Three-body recombination of helium atoms from ultracold to thermal energies: classical trajectory vs. quantal calculations

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A general method to study classical scattering in *n*-dimensions is developed. Through classical trajectory calculations the three-body recombination rate is computed as a function of the collision energy for helium atoms, as an example. The energies treated range from the ultracold up to the thermal regime. The classical results for zero total angular momentum are compared with the quantum calculations for the $J^{\Pi} = 0^{+}$ symmetry, yielding a good agreement for $E > 1$ K. The classical threshold law is derived and numerically confirmed for the three-body recombination rate. Finally, a relationship is found between the quantum and classical three-body elastic cross section at high collision energies that resembles the well-known shadow scattering in two-body collisions.

Field dependent studies of inelastic scattering properties in an ultracold mixture of lithium and metastable ytterbium

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The ultracold mixture of excited state alkaline-earth-like and ground state alkali atoms is a novel system in which to study two-body and few-body physics. Unlike the ground state of ytterbium, the long lived metastable $^3P_2$ state is predicted to support broad magnetic Feshbach resonances with the ground state of lithium, offering a promising route towards the production of ultracold heteronuclear ground state dimers with both magnetic and electric dipole moments. We report on measurements of the field dependence of inelastic scattering properties in this mixture over a wide range of magnetic fields. We also present progress towards a three dimensional optical lattice for the Li-Yb mixture. A tunable optical lattice provides useful tools to control and study collisions in our system, can enhance molecule production efficiency, and can serve as a platform for quantum simulation and information science. Additional potential studies include the use of Yb as an impurity probe of strongly-interacting Li fermions.

Measurements of Na - Na$^+$ total collision rate

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The realization of a hybrid trap, which is an ion trap overlapped with a neutral species trap, has greatly increased experimental and theoretical interest in cold ion-neutral collisional studies. The hybrid trap used by our group consists of a sodium (Na) magneto optical trap (MOT) concentric with a Linear Paul Trap (LPT) containing sodium ions. We present preliminary measurements of the total collision rate (both charge exchange and elastic) between optically dark Na$^+$ and Na and compare it with theoretical (quantal *ab-initio*) calculations of the total collision rate constant. Furthermore, we investigate the rate constant's dependence on the neutral polarizability by varying the Na MOT's average excited state population, which profoundly changes the effective polarizability. In doing so, we will also present a (two-level) model-independent study of the MOT's excited state fraction.

Dynamics of gas phase Ne*-ND_3 Penning ionization at low temperatures

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We study Penning ionization of ammonia molecules with metastable neon atoms in the range of collision energies from 0.1 to 250 K in a merged beam experiment. The reaction leads to the formation of ND_3^+ and ND_2^+, the two reaction channels differing by the ND_3 orbital from which ionization occurs. We observe a constant branching ratio for these channels over the entire energy range studied here, which spans three orders of magnitude. We also measure the total ionization rate constant. At low energies the experimental results are well reproduced by multichannel quantum defect theory calculations that rely on the long-range interaction potential. At higher energies the importance of short-range potential details is increased, which changes the collision energy dependence of the observed rates.

Few-body interactions in an ultacold Bose-Fermi mixture

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Ultracold mixture composed of different atomic spieces has become attractive today, which can expand our research range due to its more adjustable parameters. While at the same time, more experimental challenges should be solved. In this poster, we will introduce our experimental progress on the way to approach the ultracold degenerate Bose-Fermi mixture (rubidium87, pottasium40 and lithium6). Based on this experimental setup, we propose to study the two-body and three-body interactions in the ultracold mixture. As a preparation for the experiment, we will also introduce some theoretical predictions about few-body interaction in the ultracold quantum gas. For example, the width of the Feshbach resonance has a big effect on the binding energy of a molecule [1]; compared to a wide resonance, the interaction shows a surprising exotic behavior in a narrow resonance [2].

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Collisional Properties of Ultracold Radium Isotopes

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Ultracold atoms are in use for different experimental goals such as optical frequency standards, quantum degenerate gases, atom interferometry, fundamental symmetry studies and many other applications. In particular, ultracold radioactive isotopes have been in use for beta-decay studies, atomic parity violation and for searches of permanent Electric Dipole Moment (pEDM) studies. Group II alkaline earth radioactive element radium (Ra) has been proposed to be good candidate for pEDM experiment [1, 2] and also as an optical frequency standard [3]. Recently, optical dipole trapping of ultracold ^{226}Ra has been demonstrated [4]. In this context, we have calculated the elastic collisional properties and s-wave scattering lengths of the long lived bosonic and fermionic isotopes of Ra based on the available potentials and dispersion coefficients. We report preliminary results of our calculations.

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Very low power two-photon absorption in cold ^{87}Rb atoms using an optical nanofiber

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Here, we demonstrate the use of cold atoms and an optical nanofiber (ONF) to probe 2-photon absorption at a few nanowatts of powers. Apart from its spectroscopic importance, this study will be useful for all optical switching [1] and quantum logic gates at low powers. An ONF, having a subwavelength diameter, is characterized by a strong evanescent field around the waist region even when very low powers propagate through the fiber. When an ONF is integrated with a cold atom setup, this evanescent field is used to couple the cold atoms with the guided light in the ONF.

In our experiment, the ONF is fabricated by the heat-and-pull technique using hydrogen: oxygen flame [2]. Laser-cooled ^{87}Rb atoms are excited from $5S_{1/2} \rightarrow 5D_{5/2}$ via a 2-photon excitation process using $5P_{3/2}$ as an intermediate level. Using a few nanowatts of 780 nm ($5S_{1/2} \rightarrow 5P_{3/2}$) and 776 nm light ($5P_{3/2} \rightarrow 5D_{5/2}$) through the ONF, the atoms are excited to the $5D_{5/2}$ state and thereby spontaneously emit 5.2 µm ($5D_{5/2} \rightarrow 6P_{3/2}$) and 420 nm ($6P_{3/2} \rightarrow 5S_{1/2}$) photons which is coupled to the ONF itself. We detect the 420 nm fluorescence photons via the ONF and study the effects like ac Stark effect and power broadening in this process for such a system.

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A nanostructured tapered optical fiber for cold atom trapping

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Optical micro and nanofibres (MNFs) are invaluable tools for the study and manipulation of cold atoms [1]. Of particular interest is the trapping of around the MNF, for which a number of techniques have been proposed and demonstrated [2-4]. To-date, only the two-color trap [2-4] has been experimentally realized. In this configuration the forces due to the off-resonance fields of a far-detuned red and blue laser are used to create a potential to trap the atoms around the fiber. Here, we propose

a novel scheme for a tapered optical fiber-based atom trap, whereby a nanoscale slot aligned along the fiber axis is produced at its waist using focused ion beam (FIB) techniques. This change in the fiber geometry results in high evanescent field intensities both within the slot and at the external surfaces of the fiber, allowing multiple atom trapping sites to be realized through two-color trapping [5].

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Laser cooling with three-level cascade transitions: calculations for group I and II atoms and prospects for tests with calcium

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Motivated by finding alternative cooling techniques for alkaline-Earth atoms, we analyze two-color laser cooling with three-level transitions. For cascade transitions in which the upper level has longer lifetime than the intermediate one, and for cooling in “EIT regime”, using "strong" and "weak" lasers, we theoretically find that temperatures below the Doppler limits associated with each one of the individual transitions are expected [1]. Here we present estimations of temperatures as function of detunings and laser intensities for alkaline-Earth (Mg, Ca, Sr, Yb, Zn, Cd) and metal-alkaline atoms (Rb, Cs, Na), which can help guiding further experiments and stimulate additional theoretical work. We study the influence of coherences (affected by phase fluctuations between the lasers) on the final temperatures, and suggest a simpler method to estimate temperature limits in terms of dressed states decay rates. We will also present our progress towards experimental tests in a calcium MOT.

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Atomic Interactions with a Bichromatic Field: Stimulated Emission and Laser Cooling

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We report numerical results for interactions of a two level atom with the bichromatic field with the atom modelled to undergo stimulated emission only. Changes in the entropy, temperature and the atomic states present evidences laser cooling of atom in our system. The changes in the entropy of the field supports the argument for fields to be efficient reservoirs for the entropy lost by the atom. Efficiency of such cooling scheme is suggestive ideally to be Carnot efficiency limited.

Dynamics of Polychromatic Optical Forces for Deceleration of Atoms and Molecules

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To gain insight into the dynamics and limitations of coherent optical forces, we have performed numerical studies of the bichromatic force in a two-level system [1]. We discovered an improved explanation for the robustness of the force against imbalanced beam intensities. These studies also led us to develop a four-color polychromatic (4CF) variation, offering an increased velocity range and a decreased excited-state fraction. Experimental studies of the 4CF in helium are planned.

We have also numerically modeled a three-level system with a weakly coupled dark state. The bichromatic force remains effective, although it depends strongly on the power of a repumping laser. This is encouraging for applications to molecular systems, which we are exploring experimentally by utilizing the near-cycling B ↔ X transition in CaF. We are initially performing beam-deflection studies on a supersonic molecular beam, with longitudinal slowing to follow.
Support for this work provided by NSF.

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Laser Cooling without Spontaneous Emission

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It is usually presumed that spontaneous emission is necessary to remove both the energy and entropy lost by an atomic vapor during laser cooling. While this is true for monochromatic light in both Doppler and Sisyphus molasses and also in a MOT, we have shown that a multifrequency optical field itself can do both [1]. Previous bichromatic force (BF) experiments have demonstrated strong forces over a large, finite velocity range resulting in atomic beam collimation and slowing [2,3]. Our BF experiment uses the 2^3S-3^3P transition in helium at λ=389 nm, and its short duration (180 ns) precludes multiple spontaneous emission events (3^3P lifetime is 106 ns). The resulting atomic velocity distributions are shifted by very many atomic recoils, verifying that the force derives from multiple, rapid, stimulated processes. Removing the need for spontaneous emission allows laser cooling without the usual requirement for cycling transitions.

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Localized Interactions between Laser-cooled Atoms and Optical Near-field

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Precise manipulation of laser-cooled atoms near surfaces is a powerful technique for the accurate detection of atoms-surface interactions [1, 2]. We have experimentally studied higher-order interactions between laser-cooled atoms and an optical near-field. We have prepared laser-cooled ^{85}Rb atoms in crossed far-off resonance traps and loaded them into an optical near-field region near a glass surface. We report on interactions between atoms and glass surfaces using precise controlled optical dipole force traps. Additionally, we have calculated numerically higher-order interactions of atoms and an optical near-field.

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Surface Science with Trapped Ions

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We present efforts to characterize electric field noise at the surface of an ion trap [1]. A novel setup, combining the ion trap with surface analysis tools, allows for studies of the surface composition and cleaning of the trap combined with precision measurements of surface noise using a single ion as the electric field noise sensor. Reducing noise levels by identifying and targeting the cause will allow for advancement in the use of ion traps for scalable quantum computing, as well as other noise sensitive applications.

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Towards a MOT of CaF

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We report on our progress toward laser cooling and magneto-optical trapping (MOT) of CaF molecules. In this experiment, we use a two-stage buffer-gas cooled beam source to produce a cold and slow beam of CaF with an average forward velocity of 60 m/s [1]. We plan to load a MOT from this buffer-gas source. Similar to the steps taken for laser cooling of YO [2] and SrF [3], we will use "white-light" to slow the molecular beam below the MOT capture velocity. With the aim of depopulating magnetic dark states in the MOT, we are oscillating the trapping magnetic fields and simultaneously switching the MOT laser polarizations at a frequency of ~ 6 MHz (comparable to the natural lifetime of the CaF excited state).

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Magnetic Slowing, Optical Loading and Magnetic Trapping of CaF and K

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We demonstrate a general method for trapping magnetic molecules using few photon scattering in combination with magnetic slowing [1]. Starting from a two-stage cryogenic buffer-gas beam source, calcium monofluoride (CaF) molecules with an initial velocity of 30 m/s are slowed as they enter a 800 mK deep superconducting magnetic trap. Irreversible trap loading is achieved using optical pumping, where two scattered photons remove molecular energy and lead to trapping. We observe trapped CaF molecules in the $X^2\Sigma^+(v=0, N=1)$ state with lifetimes exceeding 500 ms, which is limited by background collisions. Potassium (K) was also trapped using the same approach with trap lifetimes beyond 9 s. Our future plans are to co-trap calcium monohydride (CaH) molecules with K atoms for studying K-CaH sympathetic cooling and the trapping of polyatomic molecules.

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Laser cooling and slowing of CaF molecules

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Producing ultra-cold and dense samples of polar molecules is a technical challenge and has been investigated with several techniques over the last decade [1]. Some of the future applications are related to quantum information, ultra-high resolution spectroscopy, tests of fundamental symmetries and ultra-cold chemistry. Laser cooling is a direct technique and can be applied to a wide range of molecules with suitable vibrational structure [2,3].

We have experimentally demonstrated longitudinal laser cooling and slowing of CaF molecules in a pulsed, seeded supersonic beam machine [4]. We have pursued a laser frequency chirp cooling experiment, where the chirp frequency rate is set in order to keep the laser in resonance during the cooling process.

Further, we present our progress towards a magneto-optical trap of CaF molecules. We start from a slow buffer gas source and plan to apply Sisyphus cooling and slowing to increase the number of trapped molecules substantially.

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MM-Wave Spectroscopy and Determination of the Radiative Branching Ratios of ^{11}Bh for Laser Cooling Experiments

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We aim to slow a supersonic, molecular beam of ^{11}BH using a Zeeman slower and subsequently cool the molecules to sub-millikelvin temperatures in a magneto-optical trap [1]. Most molecules are not suitable for direct laser cooling because the presence of rotational and vibrational degrees of freedom means there is no closed-cycle transition which is necessary to scatter a large number of photons. As was pointed out by DiRosa [2] there exists a class of molecules for which the excitation of vibrational modes is suppressed due to highly diagonal Franck-Condon factors. Furthermore, Stuhl et al. [3] showed that angular momentum selection rules can be used to suppress leakage to undesired rotational states. Here we present a measurement of the radiative branching ratios of the $A^1\Pi$ to $X^1\Sigma^+$ transition in ^{11}BH - a necessary step towards subsequent laser cooling experiments. We also perform high-resolution mm-wave spectroscopy of the J = 0 to J = 1 rotational transition in the $X^1\Sigma^+(v = 0)$ state near 708 GHz. From this measurement we derive new, accurate hyperfine constants. The measured hyperfine splittings and branching ratios suggest that it is possible to laser cool ^{11}BH molecules close to the recoil temperature of 4 μK using three laser frequencies only.

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Magneto-Optical Trapping of a Diatomic Molecule

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The magneto-optical trap (MOT) is the workhorse technique for atomic physics in the ultracold regime, serving as the starting point in applications from optical clocks to quantum-degenerate gases. Although MOTs have been used with a wide array of atomic species, realization of a molecular MOT was long considered infeasible. Here we present the first magneto-optical trap for a molecule, strontium monofluoride (SrF). Our MOT produces the coldest trapped sample of directly-cooled molecules to date, with temperature T ~2.5 mK. The SrF MOT is loaded from a cryogenic buffer-gas beam slowed by laser radiation pressure. Images of laser-induced fluorescence allow us to characterize the trap's properties. Although magneto-optical trapping of diatomic molecules is in its infancy, our results indicate that access to the ultracold regime may be possible for several molecular species, with potential applications from quantum simulation to tests of fundamental symmetries to ultracold chemistry.

Towards ultracold LiK ground-state molecules

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Ultracold heteronuclear molecules have seen increasing interest in the scientific community over the last few years [1]. Due to their large electric dipole moment of 3.6 Debye LiK ground-state molecules are particularly suited to investigate the physics of strongly-interacting dipolar quantum gases.

In our experiment [2] we create quantum degenerate mixtures of $8x10^4$ Li and $9x10^4$ K atoms. These are subsequently combined into weakly-bound molecules via Feshbach association yielding samples of around $3x10^4$ ultracold Feshbach molecules close to quantum degeneracy. A subsequent ground-state-transfer scheme using coherent stimulated Raman adiabatic passage (STIRAP) is currently being investigated. Here we present details of our setup and our transfer scheme. Further we give an update on the current experimental status.

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Dual Component ^{87}Rb and ^{41}K Bose-Einstein condensates in configurable optical potentials

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Multi-component Bose-Einstein condensates (BECs), whether composed of spin mixtures or different atomic species, present features not seen in single component gases. In particular, interactions between the components allow for more diverse superfluid behaviour. These interactions are tuneable via Feschbach resonances, enabling a host of rich behaviour to be studied [1].

We present our ongoing development of a two-component BEC, consisting of ^{87}Rb and sympathetically cooled ^{41}K, loaded into configurable optical potentials. By utilising a digital micromirror device (DMD) and high-resolution imaging system, a wide range of precise 2D potentials can be created. We propose to first use this system to study the coarsening dynamics of the miscible-immiscible superfluid transition in a flattened optical trap. Utilising high-resolution imaging of the condensates, a study of classical percolation on a DMD-produced optical lattice will be subsequently undertaken.

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MONDAY

Mixtures of Bose-Fermi superfluids

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We report on the observation of a mixture of Bose and Fermi superfluids with dilute gases of Lithium isotopes [1]. We probe the collective dynamics of this system by exciting center-of-mass oscillations that exhibit extremely low damping below a certain critical velocity. Using high precision spectroscopy of these low-lying modes we observe coherent energy exchange and measure the coupling between the two superfluids. Our observation can be captured theoretically using a sum-rule approach that we interpret in terms of two coupled oscillators.

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Designing an ultracold Yb-Li mixture with controllable interactions

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Over the last two decades ultracold atoms proved valuable to investigate basic properties of many-body physics with an unprecedented degree of control and purity. In recent years interest shifted to also include systems with impurities, a step towards the simulation of the more complex processes in real materials. We here present recent experimental progress on a quantum degenerate atomic mixture of Ytterbium (Yb) and Lithium (Li) [1] to be used for quantum simulation. Our current efforts are to establish a fine tuned control over the interspecies interaction via suitable Feshbach Resonances, a standard tool in alkali atoms experiments. We present a gravity compensated far-off resonant optical trap (FORT) to ensure good spacial overlap of the large mass-imbalance mixture. To establish controllable interspecies interactions, we strive to study the properties of predicted Feshbach resonances [2] between Yb in the excited $^3P_2$ state and Li in the $^2S_{1/2}$ ground state.

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High-Resolution Spectroscopy of Trilobite-Like States of $^{85}Rb_2$

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We present new, high-resolution spectra of low-n trilobite-like states in $^{85}Rb_2$. Trilobite states are novel long-range molecular states consisting of a ground-state atom embedded in the Rydberg wavefunction of a second atom. We utilize a bound-bound excitation to populate these states from photoassociated ultracold molecules in high-ν levels of the lowest triplet state. The excitation is stimulated by a frequency-doubled pulse-amplified CW laser for narrow linewidth, under 200 MHz. Upon excitation, the trilobite-like states rapidly autoionize and are mass-selectively detected by an ion detector. This technique gives a two orders-of-magnitude improvement over the previous excitation method, which was done by a broader linewidth conventional pulsed laser as reported in Ref. [1]. This work is supported by the NSF and AFOSR.

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The creation of ultracold RbCs molecules in the rovibrational ground state

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Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment. The anisotropic, long range dipole-dipole interactions between such molecules offer many potential applications [1], including novel schemes for quantum simulation. Here we demonstrate the creation of ultracold RbCs molecules in the rovibrational ground state. The molecules are created from a high phase space density mixture of ^{87}Rb and ^{133}Cs [2] in a two-step process. First weakly bound RbCs molecules are created using magnetoassociation on an interspecies Feshbach resonance [3]. The molecules are then optically transferred into the rovibrational ground state of the singlet potential by stimulated Raman adiabatic passage (STIRAP) following the route outlined in [4]. We report our progress towards measuring the electric dipole moment of the molecules and subsequently realising a dipolar quantum gas.

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Thermalization and progress to degeneracy in a mixture of rubidium-87 and ytterbium

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Rubidium-87 has been the workhorse for degenerate gas experiments for over a decade. The large number of ytterbium isotopes and range of interactions [1],[2] available make it a promising element for a mixture with rubidium. Here we present studies of thermalization in an ultracold mixture of rubidium-87 and ytterbium in a two-color optical dipole trap [3] consisting of a 1064 nm and 532 nm beam. We characterize the properties of our trap and will describe a possible avenue for creating a degenerate mixture of these two species using a new “rubidium-blind” cross-dipole trap at 423 nm.

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Electron Dynamics and Terahertz Emission in Two-Color Photoionization

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Two-color laser photoionization has been widely used as a versatile tool for broadband terahertz (THz) generation [1-3]. The physics of THz generation is also compelling, raising fundamental questions about the interaction of strong electromagnetic fields with atoms and molecules in the nonperturbative regime. Microscopically, THz generation arises from the evolution of laser-driven electron wavepackets in a strong electric field and their transition from atomic to plasma states [2-3]. To verify such a microscopic detail, we apply a dichroic interferometry method to measure the relative phase at the focus. Simultaneously, we observe electric currents arising in the vicinity of the focus where THz radiation originates. Our results show that both THz fields and electric currents peak at a relative phase of π/2, consistent with the semiclassical plasma current model. This indicates that electron-ion scattering does not significantly affect THz radiation in the tunnel ionization regime.

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Electron-Rescattering from Ar and Xe induced by Intense Laser Filed: Above Threshold Ionization and Rydberg Excitation

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Electron-rescattering with ionic core plays a key role in atom-strong-field physics, which may lead to high-order above threshold ionization (HATI, elastic rescatteing), non-sequential double ionization (NSDI, inelastic rescatteing), high-order harmonic generation (HHG, radiative recombination), or even Rydberg excitation. Here, we performed experimental studies on several rescattering-related processes of Ar and Xe atoms. We observed fine ATI structures in the 2-D electron momentum, which are dependent on both laser intensity and wavelength obviously. The results indicate that channel close or resonance effect could be significant in ATI process. By measuring the yield of neutral Rydbergs as a function of laser intensity, we observed the "knee" structure in Rydberg excitation, similar as in NSDI but less dependent on the laser ellipticity, which indicates a "soft-rescattering" in Rydberg excitation. The study could provide further understanding for the electron-rescattering of atoms in strong laser fields.

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MONDAY

Benchmark H_2 few-cycle photoionisation measurements and laser intensity calibration with percent-level accuracy

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Photoionisation of atoms and molecules from intense few-cycle laser pulses is the source of many strong-field phenomena that have been used to image molecular dynamics [1], probe electron localization [2] and measure the laser carrier-envelope phase [3]. Correct experimental observation and interpretation of such highly non-linear effects thus requires both highly accurate data and knowledge of the laser peak intensity. We present benchmark photoionisation measurements for molecular hydrogen (H_2) that is certified by excellent theory-experiment agreement for atomic hydrogen (H). Our results in H_2 provide an order-of-magnitude improvement in reference data for simulations of complex strong-field phenomena, and serves as a stringent test for molecular theories of strong-field ionisation. Building upon previous work [4], we incorporate our H_2 data into an easily accessible technique for calibrating the laser peak intensity to an accuracy of 3%. This technique can be readily applied to intensity calibrate almost any few-cycle strong-field experiment.

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Ionisation of metastable states of neon using few-cycle light fields

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We present results for experiments involving the ionisation of metastable neon (Ne*) using ultra-short (sub-6fs) laser pulses. The study of interactions between ultrafast light and matter is topical due to the broad range of effects that can be observed [1-3]. We utilise a DC discharge type source to generate Ne* atoms which interact with the laser pulses in a Cold Target Recoil Imaging Spectroscopy device, which records time of flight and maps the momentum of Ne ions created in the interaction. We will present ion yields for laser pulses with intensities ranging from 10^{13}-10^{15}W/cm^2 and compare this data to current theories.

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Characterisation of intense few-cycle laser pulses from photo-ionisation of atomic hydrogen

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The photo-electron spectra produced by the interaction of atomic hydrogen with an intense few-cycle laser pulse can provide a useful means of obtaining accurate information about the incident laser pulse. In particular, comparison of simulated and experimental results allows for measurements of peak laser intensity – a parameter which is difficult to measure directly, but which is crucial for evaluating experimental results in strong field physics. These comparisons require a large number of computationally demanding simulations that are capable of reproducing photo-electron spectra to arbitrary accuracy. The simulations must be able to adequately account for pulse-to-pulse variation in the laser field and varying intensity across the profile of the laser beam. We demonstrate how a single atom photo-electron spectrum is sensitive to variation in the laser field by comparing simulated spectra for different carrier-envelope phases and intensities. We show that these results give good agreement with experimental data.

MONDAY

Strong-field ionization of helium by elliptically polarized light in attoclock configuration

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We perform time-dependent calculations of strong-field ionization of He by elliptically polarized light in configuration of recent attoclock measurements [1]. By solving a 3D time-dependent Schrödinger equation, we obtain the angular offset Θ of the maximum in the photoelectron momentum distribution in the polarization plane relative to the position predicted by the strong field approximation. This offset is used in attoclock measurements to extract the tunneling time. Our calculations [2] clearly support the set of experimental angular offset values obtained with the use of non-adiabatic calibration of the *in situ* field intensity, and disagree with an alternative set calibrated adiabatically. These findings are in contrast with the conclusions of Ref. [1],that found a qualitative agreement of semiclassical calculations with the adiabatic set of experimental data. This controversy may complicate interpretation of the recent atto-clock measurements [3-4].

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Improving conversion efficiency of high harmonic generation with gas mixtures

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We report an improvement of the conversion efficiency of the fundamental IR light into XUV high harmonic photons by using mixtures of two gases (H_2 and Ne) with significantly different ionization potentials (IP). The initial high harmonic generation (HHG) takes place in the component with low IP, inducing excited states and facilitating ionization and HHG in the component with high IP [1]. We observed up to a 2.5 fold enhancement of HHG compared to pure H_2 and up to $3x10^3$ enhancement compared to pure Ne at moderate laser intensities at the gas jet ~$1.5x10^{14}$ W/cm^2 . Thus, mixing of gases with low and high ionization potentials opens up new possibilities for the efficiency enhancement of the HHG process.

This work was supported by the Robert A. Welch Foundation Grant No. A1546 and the Qatar Foundation under the grant NPRP 5 - 994 - 1 – 172.

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Signatures of field-induced intramolecular quantum interference in high-order harmonic generation by laser-irradiated homonuclear diatomic(s)

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MONDAY

The strong-field phenomenon of high-order harmonic generation (HHG) in laser-irradiated homonuclear diatomic species (H_2^+, H_2) is studied theoretically under conditions corresponding to intermediate values of the so-called *Keldysh parameter* ($\gamma \leq 1$). The problem is addressed within the *length-gauge* formulation of molecular *strong-field approximation* (SFA) [1] complemented with the *density-functional-theory* (DFT) applied for numerical composition of initial (laser-free) molecular state using the routines of GAUSSIAN-03 code [2]. Our DFT-SFA calculation results well reproduce and suggest a pronounced interference-related minimum arising in high-frequency region of respective molecular HHG spectra that evidently demonstrate the clear signatures of the field-induced *intramolecular* interference [3] of strong-field ionization amplitudes corresponding to photoelectron emission from different atomic centers. In particular, the location of the minimum proved to be very sensitive to the laser wavelength λ and the angle Θ of molecular axis orientation with respect to the laser field polarization as well as to internuclear separation R_0.

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Quantum Optics and Cavity QED Mo-066

Coherent population trapping (CPT) coupled by magnetic dipole interactions

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We report our study on CPT driven by magnetic dipole interactions. We consider a Λ system consisting of a pair of Zeeman sublevels in one hyperfine level and another sublevel in the other hyperfine level coupled by a pair of radio-frequency fields. We use lithium atoms in an optical trap for our experimental study. The system allows independent control of the main parameters characterizing CPT. Moreover, by turning off the applied fields, the system is frozen so that its quantum state can be measured precisely. We studied the line shapes and dynamics of the CPT system, and measured the phase relation of the dark superposition state to find excellent agreement with theory. The possible application of the scheme as a method to cool optically trapped atoms below the recoil limit in a manner analogous to velocity-selective coherent population trapping is to be discussed.

Quantum Optics and Cavity QED Mo-067

High Conversion Efficiency in the Resonant Four-Wave Mixing Process

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We systematically studied the energy loss and conversion efficiency in four-wave mixing (FWM) processes. The FWM can be used to convert probe light into signal light with the presence of the coupling and pump fields experimentally; In order to determine the condition, we design two specializing FWM systems and find the relationship between system response time and coupling rising time. Based on this study, we propose a scheme that in the steady state the input probe can be nearly 100% converted to output signal with negligible energy loss. The proposed scheme is very useful for the sum frequency generation and can significantly advance the technology in nonlinear optics.

Dynamics of strongly interacting photons in waveguides: a generalized input-output formalism

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We present a generalized input-output formalism to describe the propagation of strongly interacting photons through an atomic ensemble. Standard approaches typically involve approximations to eliminate the atomic degrees of freedom, to subsequently arrive at a nonlinear field equation describing the optical modes. On the contrary, we show that, by effectively integrating out the photonic field, a spin model containing only discrete atomic degrees of freedom can be obtained. Then by explicitly solving for the atomic dynamics, the optical fields are reconstructed exactly, including S-matrix and any correlation function. Our approach to provide a complete description of the system dynamics represents a powerful tool to explore a wide range of new phenomena in nonlinear quantum optics. We discuss the formalism in several experimental situations.

Coherent population trapping in a two field cavity-QED system: Semiclassical Theory

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We calculated the steady state transmission and reflection spectra of coherent population trapping (CPT) in a two field cavity-QED system consisting of few to many three-level atoms coupled with two longitudinal modes of an optical cavity. In this scheme, both the probe beam and the coupling beam have comparable intensities and are coupled into the same cavity, driving corresponding intra-cavity field. Results are presented with different coupling beam detuning under different atom number and light intensities. Meanwhile we discussed the conditions required to realize two field intra-cavity CPT. We also find that small cavity detuning has little influence to the presence of CPT, which renders the system feasible in experimental realization with current technology.

Coherent coupling of hybrid alkali vapor through spin-exchange collisions

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Spin-exchange collisions are a major decoherence process in warm alkali vapor, as they induce random transitions between the hyperfine levels. However, at very low magnetic fields, the evolution of a spin-polarized ensemble effectively becomes spin-exchange relaxation-free (SERF) [1]. Here we study experimentally and theoretically a hybrid system of two alkali species, in which one specie inherits the magnetic properties of the other. We demonstrate that spin-exchange collisions induce a transfer of coherence between potassium and rubidium at low magnetic fields. We show that the potassium atoms inherit the gyromagnetic ratio and the life time (T1) of the rubidium atoms. As a result, the elimination of spin-exchange relaxation for the potassium atoms survives up to a much higher magnetic field threshold, corresponding to the rubidium's threshold. We explain these phenomena analytically by the hybridization of the two species via the spin-exchange interaction.

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Quantum Optics and Cavity QED Mo-071

Observation of Paired Superradiance

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A single photon (E1) emission rate is greatly enhanced by using a material coherence. This phenomenon is known as "Superradiance". The enhancement of the emission rate is proportional to N^2, where N is a number density of atomic ensemble. A two-photon emission rate from metastable state of atoms/molecules may also be greatly enhanced by use of such "macroscopic coherence". We proposed this macro-coherent enhanced two-photon emission process as "paired superradiance" [1]. Similar proposal of effective parametric down-conversion was proposed by Harris [2]. However, to our knowledge, there is no experimental demonstration of paired superradiance so far.

In this poster, we report the observation of paired superradiance. We prepared a large coherence between ground and vibrational excited state of para hydrogen molecules by adiabatic Raman process; and observed two-photon emission from excited state. About 10^{19} enhancement of emission rate is obtained. Updated results and detailed analysis will be presented.

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Cavity QED in the Recoil Resolved Regime

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We are experimentally exploring the light matter interaction of a Bose-Einstein condensate with a high finesse optical standing wave cavity with a Purcell factor far above unity. The unique feature of our cavity is its extremely small linewidth comparable to the single photon recoil frequency. As a consequence, cavity assisted scattering can only occur in a narrow resonance window such that only very few selected motional states are coupled. We discuss recent experiments showing sub-recoil cavity cooling [1], extreme non-linear collective behavior, like optomechanical hysteresis and bistability [2], and superradiance - or self-organization instabilities related to the Hepp-Lieb-Dicke phase transition.

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Nonequilibrium phase transitions in periodically-driven cavity QED systems

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Ensemble of atoms confined in an optical cavity displays several collective phenomena. In equilibrium, the system exhibits the Dicke transition associated with the symmetry breaking. Under the time-periodic driving such as laser irradiation, it is known that the system shows the optical bistability and undergoes the discontinuous transition without the symmetry breaking.

Here we report our theoretical discovery on the new kind of phase transitions with symmetry breaking in the ultra-strong coupling and driving regime [1]. We argue that these transitions are understood by the concept of coherent destruction of tunneling, which is a simple quantum interference effect under the time-dependent external field.

We will also discuss about the effect of finite system size by performing the $1/N$ expansion.

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MONDAY

Strong atom-light interactions in 1D photonic crystals

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Nano- and microscale optical systems have shown great progress towards realizing efficient and scalable quantum interfaces through enhanced atom-field coupling in both resonators and waveguides [1]. Beyond these conventional topologies, new opportunities emerge from the integration of cold atoms with nanoscale photonic crystal devices. In photonic crystal waveguides (PCW), light-matter interaction can be engineered for both trapping and strong atom-photon interactions [2], enabling exploration of novel quantum transport, quantum many-body phenomena, and Casimir-Polder forces [2-4]. We have developed an integrated optical circuit with a PCW capable of both localizing and interfacing atoms with guided photons. From reflection spectra measured with average atom number of 1.1 (0.4), we infer the fraction of single-atom radiative decay into the PCW to be $\Gamma_{1D}/\Gamma' = 0.32\ (0.08)$, where Γ_{1D} (Γ') is the atomic spontaneous emission rate into the guided (all other) mode (s) [5]. We discuss progress towards trapping atoms within the PCW, which should enable a regime where $\Gamma_{1D}/\Gamma' \sim 10$.

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Crossover from Lasing to Photon Bose-Einstein condensation by Photon Gas Thermalization

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Thermal equilibrium is the condition most frequently found in cold gases and solid-state physics. In general however, driving and loss can force a system away from equilibrium. A prominent example for the emergence of an ordered state in nonequilibrium physics is the laser, where one engineers photon loss inside a cavity to achieve a large population of the desired optical modes. Interestingly, such an ordered photon state is also achieved with a thermal equilibrium phase transition, by Bose-Einstein condensation. We report the observation of a crossover between a lasing state and a photon condensate in a dye microcavity by in-situ monitoring the photon dynamics. When thermalization to the dye temperature by absorption and re-emission of photons is faster than their loss, photons accumulate at low energy states near the cavity cutoff and form a Bose-Einstein condensate. In contrast, when photons leave the cavity before they thermalize, the system remains in e.g. a mode-locked laser state.

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Fiber cavity-based photon-ion interfaces

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Strong light-matter interaction is a key ingredient for a number of linked quantum system applications, such as entanglement distribution, quantum simulation, and distributed quantum computing. Our approach to this research area combines fiber-based cavities with ion traps [1], aiming to capitalize on both the benefits of high-finesse cavities and the established quantum control of trapped atomic ions. For this we trap Yb-ions in specialized Paul-type ion traps that address the challenges of tightly placed dielectric materials close to the ion, while keeping scalability of the system as a major design goal in mind. The poster will present our recent progress in using these systems as intrinsically fiber-coupled efficient single photon sources. We show polarization-spin state correlation and polarization dependent absorption demonstrating the feasibility of using our system as quantum network node.

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Building a hybrid quantum system of neutral atoms coupled to a superconducting circuit

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One avenue for creating hybrid quantum systems is the coupling of a neutral atomic ensemble to superconducting circuits via a magnetic dipole transition. Here we present progress towards trapping cold rubidium atoms within 10 micrometers of a superconducting circuit using a cryogenically-compatible atom trap and a tunable, light-insensitive, high-Q superconducting resonator. Evanescent fields around an optical nanofiber with 99.95% transmission form an atom trap suitable for a 10 mK dilution refrigerator. We systematically study how low levels of optical light scattered from a tapered fiber positioned near the superconducting resonator affect its linewidth and frequency.

Work supported by NSF, the Atomtronics MURI, and the PFC at JQI.

Atom induced cavities and tunable long-range interactions between atoms trapped near photonic crystals

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The use of cold atoms to simulate strongly interacting quantum systems is rapidly progressing. However, achieving tunable, coherent, long-range interactions between atoms is challenging, leaving a large class of models inaccessible to quantum simulation. We propose a solution exploiting the powerful new platform of cold atoms trapped near nano-photonic systems. We show that atoms trapped near photonic crystals act as dielectric elements that seed localized cavity modes around each atom. In a dynamic form of 'all-atomic' cavity QED, the length of these cavity modes can be tuned, and atoms separated by the order of the effective cavity length can interact coherently with each other. Considering realistic conditions such as fabrication disorder and photon losses, coherent long-range potentials or spin interactions can be dominant in the system over length scales up to hundreds of optical wavelengths. These systems may be used to study long-range interactions in many-body atomic systems as well as to realize effective long-range interactions between photons for non-local, non-linear optics.

2-D spectrum of an optical microcavity coupled to a few atoms

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Past studies [1, 2] have demonstrated a fibre-coupled optical microcavity for high-cooperativity cavity quantum electrodynamics in the fast the cavity regime, where $\kappa > g > \gamma$ (κ is cavity decay rate, g is atom-cavity coupling, γ is atom decay rate) and $g2 > \kappa * \gamma$. To complete the understanding of such systems, we have measured the 2-D spectrum that covers both atom-laser detuning and cavity-laser detuning, observed both in reflection from the cavity and in fluorescence from the atom excited through the side of the cavity. Although the coupled atom-cavity system is not in the strong coupling regime, we observe a strong dispersive splitting in the 2-D reflection spectrum and not in the fluorescence spectrum.

The experiment comprises a ^{87}Rb Magneto-optical trap (MOT) and a microcavity, which is formed between a micro-spherical-mirror array chip and a plane mirror-coated fibre tip. The ^{87}Rb atoms are trapped, cooled and pushed into the microcavity, which is locked to a stable single frequency laser, whose frequency is simultaneously monitored by a wavemeter with 100 MHz precision. As the atoms enter, they are pumped either through the fibre or transversely through the side of the cavity. The 2-D spectra are measured by scanning both pump laser and cavity resonance frequency. The measured spectra are compared with a theoretical model, which allows us to understand why the reflection spectrum exhibits anticrossing, while the fluorescence spectrum does not.

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MONDAY

Graphene plasmons quality factors

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Plasmons in graphene hold great potential for applications since they enable strong confinement of electromagnetic energy at subwavelength scales [1]. This confinement results in strong light-matter interaction at the single photon level, like the high decay rates and vacuum Rabi splittings of quantum emitters in the proximity of the graphene sheet [2]. However all of these exciting effects depend on the quality factors of plasmons. Since they live in a complicated solid state environment, there are numerous excitations that can reduce the quality factors. In my poster I will present our work on the various scattering mechanisms and plasmon damping. Particularly I will focus on the interaction of plasmon with optical phonons, since this process gives an intrinsic limit on the plasmon quality factor at infra-red frequencies [1]. Moreover I will discuss a screening effect on the optical scattering rates for charge impurity scattering and surface polar phonon scattering [3].

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Quantum Optics and Cavity QED Mo-081

Single-photon second-order nonlinear processes in graphene

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Intense efforts have been made in recent years to realize nonlinear optical interactions at the single-photon level. Much of this work has focused on achieving strong third-order nonlinearities, such as by using single atoms or other quantum emitters, while the possibility of achieving strong second-order nonlinearities remains unexplored. Here, we describe a novel technique to realize such nonlinearities using graphene, exploiting the strong per-photon fields associated with tightly confined graphene plasmons in combination with spatially non-local nonlinear optical interactions. Under realistic conditions, we show that the interactions are strong enough to observe the generation of non-classical light and allow near-deterministic down-conversion of a single plasmon into an entangled plasmon pair.

Room temperature coherent population trapping with nuclear spins in diamond

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Nuclear spins are attractive candidates for solid-state quantum information storage and processing owing to their extremely long coherence time [1]. However, since this appealing property results from a high level of isolation from the magnetic environment, it remains a challenging task to polarize, manipulate and readout individual nuclear spins [2].

In this work, we show room temperature coherent population trapping with nuclear spins in diamond using single nitrogen-vacancy defect. We investigate sequential building of the dark state and we use this effect to demonstrate a polarization process of nuclear spins. This mechanism, which operates in the microwave domain, could find applications in solid-state quantum information and in micro-wave photon storage.

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Coherent spin control of a nanocavity-enhanced qubit in diamond

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A central aim of quantum information processing is the efficient entanglement of multiple stationary quantum memories via photons [1-3]. Among solid-state systems, the nitrogen-vacancy (NV) centre in diamond has emerged as an excellent optically addressable memory with second-scale electron spin coherence times [4,5]. Recently, quantum entanglement and teleportation have been shown between two NV-memories [6–8], but scaling to larger networks requires more efficient spin-photon interfaces such as optical resonators [9]. Here, we demonstrate such NV-nanocavity systems with optical quality factors approaching 10,000 and elec- tron spin coherence times exceeding 200 µs using a silicon hard-mask fabrication process. The on-chip integration of our system with microwave circuits for coherent spin control provides a compact architecture for quantum repeaters [10], spin-based microprocessors [11], and quantum networks [12].

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Size-dependence of radiation power thermally emitted from a microparticle

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MONDAY

Although Planck's law of blackbody radiation well describes spectral profiles of thermal radiation from macroscopic objects, it remains an open question if Planck's formula applies to particles of size comparable to optical wavelengths. Our laser-trapping technique spacially and thermally isolates a high-temperature particle in the Mie regime, and enables emission spectroscopy of the single particle [1]. Thermal radiation spectrum from a dielectric microsphere exhibits sharp resonances with whispering gallery modes of the spherical resonator. Measurements of the mode spacing provide precise data of the particle size and size-dependence of the emission spectra. Total radiation power emitted from a macroscopic object linearly depends on its surface area. In contrast, our analysis of the microparticles reveals cubic dependence of the emission power on the particle size, showing a micron-sized dielectric particle is a volume emitter where not only its surface but atoms inside contribute to the thermal radiation.

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Experimental Realization of Environment Assisted Speed Up of the Quantum State Evolution in the Open Quantum System

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Manipulation of the quantum speed of the state evolution is important in quantum information and quantum engineering. We have experimentally measured the quantum speed of the state evolution in the open quantum system (optical cavity QED system) under weak driving. We consider the system the mode of the electromagnetic field with a preferential coupling to a tunable environment: the atoms. By controlling the environment, i.e. changing the number of atoms coupled to the optical cavity mode, we can experimentally realize the environment assisted speed up of the quantum state evolution in the optical cavity. And our result demonstrates that the quantum speed of the state re-population in the optical cavity increases, as the interaction between the optical cavity mode and the environment (the number of atoms) increases. Work is supported by NSF.

Modal decomposition and control of higher-order modes in silica nanofibers

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Atoms confined in optical nanofiber evanescent-field traps experience strong coupling to photons propagating through the fiber. This strong coupling is ideal for quantum technologies and sensors. Strong atom-photon interactions have been demonstrated in fibers with submicron diameters, small enough to admit only the HE_{11} mode. Higher-order vector modes open another set of trapping geometries in fibers with diameters above the HE_{11} cutoff value. We have previously achieved 97% transmission of the first excited mode family, which contains the TE_{01}, TM_{01}, and HE_{21} modes, but due to their near degeneracy, excitation of a pure mode within this family in the nanofiber waist is challenging. In this work, we discuss techniques to measure mode purity through modal decomposition of the output field and analysis of Rayleigh scattering in the waist. This work was funded by ONR, the ARO Atomtronics MURI, DARPA, and the NSF through the PFC at JQI.

QUANTUM INFORMATION

Entanglement Generation in a Multi-Qubit System Coupled to Heat Bath

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The entanglement generation in a multi-qubit system interacting with heat bath and an external local magnetic field is investigated in the framework of the master equation. The time-evolution for the most general density matrix of the multi-qubit system is obtained and solved. It is shown that the two-qubit system ends up in an entangled stationary state independent on the initial separable state.

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MONDAY

Quantum storage based on the control field angular scanning

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Continuous change of the propagation direction of a classical control field in the process of its off-resonant Raman interaction with a weak signal field in a three-level atomic medium is suggested for quantum storage of a single-photon wave packet. It is shown that due to the phase matching condition such an angular control allows one to reversibly map the single-photon wave packet to the Raman spatial coherence grating. Thus, quantum storage and retrieval can be realized without using inhomogeneous broadening of the atomic transitions or manipulating the amplitude of the control field. Under some conditions the proposed scheme proves to be mathematically analogous to the quantum storage scheme based on controlled reversible inhomogeneous broadening of the atomic states [1].

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Time-Continuous Bell Measurements

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We combine the concept of Bell measurements, in which two systems are projected into a maximally entangled state, with the concept of continuous measurements, which concerns the evolution of a continuously monitored quantum system. For such time-continuous Bell measurements we derive the corresponding stochastic Schrödinger equations, as well as the unconditional feedback master equations [1]. Our results apply to a wide range of physical systems, and are easily adapted to describe an arbitrary number of systems and measurements. Time-continuous Bell measurements therefore provide a versatile tool for the control of complex quantum systems and networks. As examples we show that (i) two two-level systems can be deterministically entangled via homodyne detection, tolerating photon loss up to 50%, and (ii) a quantum state of light can be continuously teleported to a mechanical oscillator, which works under the same conditions as are required for optomechanical ground-state cooling.

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A Monte Carlo wavefunction method for semiclassical simulations of spin-position entanglement

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Many simulations of atoms are semiclassical: they simulate the internal state of atoms quantum mechanically, but positions and momenta classically. Laser cooling, for example is simulated in this way. However a conflict arises when the force on an atom depends on its internal state. Actual atoms in a superposition of spin states in a magnetic field gradient, for example would move in multiple directions, resulting in spin-position entanglement, which can't be modelled semiclassically.

I describe a Monte Carlo wavefunction method that resolves this conflict by considering the resulting entanglement to be a quantum measurement, and using decoherence to include it as a probabilistic jumping between different spin states of the atom as it follows only one classical trajectory through space.

Individual Addressing of Trapped Ions with MEMS-based Beam Steering

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Scalability is one of the major challenges of trapped ion based quantum computation, mainly limited by the ability to manipulate an increasing number of qubits. For individual addressing of qubits, microelectromechanical systems (MEMS) technology allows one to design movable micromirrors to focus laser beams on individual ions and steer the focal point in two dimensions [1]. This system provides low optical loss across a broad wavelength range and can scale to multiple beams.

Using a microfabricated surface trap from Sandia National Laboratories we trap chains of $^{171}Yb^{+}$ ions. Using MEMS mirrors, we perform single qubit gates on individual $^{171}Yb^{+}$ ions in a chain with Raman transitions driven by stabilized frequency combs [2]. Using this setup, we sequentially perform single qubit gates on multiple qubits and characterize gate performance using quantum state tomography. Our system features negligible crosstalk to neighboring ions, and switching speed comparable to typical single-qubit gate times.

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Quasiparticle engineering and entanglement propagation in a quantum many-body system

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The key to explaining and controlling a range of quantum phenomena is to study how information propagates around many-body systems. Quantum dynamics can be described by particle-like carriers of information that emerge in the collective behaviour of the underlying system, so called quasiparticles. Here, we experimentally study quasiparticle dynamics observed in a quantum many-body system of up to 20 trapped atomic ions with a tunable interaction range. Making use of a tightly focused laser beam to address individual ions and single-ion resolved imaging, we investigate and characterize the propagation of entanglement distributed by specifically engineered quasiparticles in different experimental regimes [1]. We further perform quantum state tomography of subsets of the full chain in order to investigate the possibility of an efficient representation of the full quantum state using matrix product states and -operators [2,3].

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Femtosecond Ramsey interferometry for atomic qubit state measurement

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Experimental demonstration of ultrafast optical implementation of all three angular rotations (x-, y-, and z-rotations) of single qubits composed electronic states of cold rubidium atoms is presented. The spatial confinement of cold rubidium (Rb) atoms in a magneto-optical trap has enabled uniform nonlinear interaction of ultrafast lasers with the atomic ensemble, or high-fidelity Rabi oscillations. Aside from the usual Bloch sphere rotation about x-axis to say, the other two angular rotations are constructed, respectively, by carrier-envelope phase control and far-off resonant strong-dispersive interaction. All the interactions are induced by shaped ultrafast laser pulses, permitting operations on a sub-picosecond time scale or at terahertz speeds. For the phase evolution measurement of the Bloch vector, we used laser-pulse shaping technique to facilitate femtosecond Ramsey interferometry.

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Quantum Simulation of Unphysical operation with a Trapped Ion

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We report on the experimental quantum simulation of unphysical symmetry operations such as complex conjugation, charge conjugation and time reversal with a trapped ion [1]. In particular, we focus on anti-unitary operations in the context of Majorana Equation. Generally, quantum operation is unitary and it is considered to be impossible to implement an anti-unitary operation in quantum system. We experimentally study the interesting various phenomena in Majorana equation with a single 171^Yb^{+} ion in an enlarged Hilbert space based on the proposal in Ref [1]. Quantum simulation may eventually provide a solution to a certain complex problem that is intractable with classical computation. In our study, we explore the other aspect of quantum simulation, where it brings purely theoretical or imaginary concepts to the table top experiment.

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Propagation of information in long-range interacting quantum lattice system.

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Propagation of information in short-range interacting systems is restricted to within a linear "light cone", as proven by the well-known Lieb-Robinson bound, thus ensuring a well defined notion of locality. Whether long-ranged interactions can lead to a different shape of this light cone, and the breakdown of the associated notion of locality, is an important but largely unexplored question. We will present our theoretical progress towards a complete understanding of locality in long-range interacting systems, and especially how, as the interaction range shrinks, locality is recovered [1].

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Single phonon addition to thermal mechanical motion of trapped ion

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We propose schemes for generation of nonclassical motional states of a single trapped ion and present our progress towards realization of ion trapping apparatus for their experimental tests.

We analyze dynamics of red and blue-detuned spin-oscillator couplings and conditional operations of phonon subtraction and addition to the thermal state of motion. We provide estimations of observability of negative Wigner distribution in realistic experimental conditions. By driving initially excited two-level system coupled to a harmonic oscillator on a blue motional sideband and realizing projective measurement on the electronic ground state, a single excitation can be added to the state of the oscillator. Motional state becomes highly nonclassical even for initially thermal distribution and for imperfect projective measurements, which is demonstrated by large negative values of the Wigner function.

MONDAY

Quantum Computing with Ba and Yb Ion Chain

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Building a quantum computer requires individual addressing and coherently controlling qubits. Benefiting from long lived internal states and motional states, trapped ions are very good candidates for quantum computing and quantum information tasks. The ion chain with different species, reducing the crosstalk between ions, may improve the fidelity of quantum operations. Using high intensity, ultrafast laser pulse to manipulate the quantum states, the speed of quantum computing can be significantly increased. In our experiments, we trap mixed Ba/Yb ion chains in linear ion traps (macroscopic and chip-scale microfabricated), to realize basic quantum operations.

Ultrafast entanglement of trapped ions

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We have demonstrated ultrafast spin-motion entanglement of a single atomic ion using a short train of intense laser pulses. This pulse train gives the ion a spin-dependent kick where each spin state receives a discrete momentum kick in opposite directions. Using a series of these spin-dependent kicks we can realize a two qubit gate. In contrast to gates using spectroscopically resolved motional sidebands, these gates may be performed faster than the trap oscillation period, making them potentially less sensitive to noise. Additionally this gate is temperature insensitive and does not require the ions to be cooled to the Lamb-Dicke limit. We show that multiple kicks can be strung together to create a ``Schrodinger cat'' like state, where the large separation between the two parts of the wavepacket allow us to accumulate the phase shift necessary for a gate in a shorter amount of time. We will present a realistic pulse scheme for a two ion gate, and our progress towards its realization.

MONDAY

Population transfer collisions involving nD Rydberg atoms in a CO_2 optical dipole trap

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There has been an increasing interest in cold Rydberg atoms over the last several years. The primary reason for this attention is that interactions between Rydberg atoms are strong and lead to many interesting and useful phenomena, which require high atomic density samples. In this work, we have loaded Rb atoms into a CO_2 optical dipole trap. After the loading, we turn off the dipole trap and excite the Rydberg state using a combination of two cw laser beams at 780 nm and 480 nm respectively. Finally, the Rydberg atoms are detected using pulsed field ionization technique. By analyzing the electrons signal, we can study the population transfer from the nD state to the (n+2)P as a function of the atomic density for $37 \leq n \leq 45$. As the atomic density increases, the excitation of the nD state saturates, suggesting the occurrence of dipole blockade. Nevertheless, the (n+2)P is quadratically proportional to the nD population. We have also investigated the role of a dc electrical field in such process. This work was supported by Fapesp and INCT-IQ.

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Aggregation of Rydberg excitations in a dense thermal vapor cell

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Interacting Rydberg atoms in dense gases are of growing interest, due to new physics enabled by the Rydberg blockade effect. Among others, strongly interacting many-body systems with Rydberg atoms were recently studied in cold atomic gases [1][2]. Here we consider a very dense gas of thermal atoms at room temperature excited off-resonantly to a Rydberg state. At a certain distance of an already excited atom the excitation of another atom is facilitated, since the interaction compensates the laser detuning [3]. This allows for the creation of Rydberg aggregates growing exponentially from their boundaries.

We present our experimental results on the creation of such Rydberg aggregates in a vapor cell. We are able to monitor the growth dynamics of the aggregates in time and extract scaling laws for the characteristic timescale. Our findings are consistent with a model based on an effective Master equation.

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Design and simulation of a cold Rydberg atom production and detection system.

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The design of an experimental system to produce and detect cold Rydberg atoms is presented. We plan to use a three-photon excitation scheme to produce nf states of atomic rubidium. The geometrical constraints imposed by the CAD design are then used in simulating programs for the parameters of the magnetic quadrupole trapping field and the shape of the intersection between the magneto-optical and the three laser beams responsible for the excitation. Simulations are also used to design the electric field applied to parallel plates that will be used for field ionization. The study of ion trajectories for the time of flight detection of the Rydberg atoms is also presented.

3-body resonant interaction in cold Cs Rydberg atoms

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Cold Rydberg atoms are a promising tool for studying few-body and many-body interaction because of their strong and long-range dipole-dipole interactions. One example is Förster resonance, a 2-body energy exchange resonance [1] analogous to FRET in biology [2].We have observed 3-body Stark-tuned resonances in a cold Cs Rydberg gas for different principle quantum number n, described by the following equation:

$3xnp_{3/2}\ m_J=1/2(m_J=3/2) \leftrightarrow (n+1)s + ns + np_{3/2}\ m_J=3/2(m_J=1/2)$.

We excite the Rydberg state via a three-photon excitation starting from a Cs MOT, tuning the resonance with an external electric field [3]. This new FRET process could be used to design a 3-Qbit quantum gate or to provide an effective Quantum Non Demolition measure of entanglement between 2 atoms, measuring the 3rd. It could improve imaging techniques in biology that already use 2-body FRET [2] and new solar cell technology which already tries to mimic light-harvesting that is ruled by FRET.

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MONDAY

Quantum simulations of biochemical processes with Rydberg atoms

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Excitation transport through resonant dipole-dipole interactions is a fundamental feature that is shared by arrays of ultra-cold Rydberg atoms and biological light-harvesting complexes. This can be exploited twofold:

Firstly, we show that quantum simulations of light-harvesting processes are possible with an aggregate of Rydberg atoms embedded in- and monitored by a background cold gas [1]. Determining the location of excitation energy in the system decoheres quantum excitation transport. We thus can engineer an open quantum system with tuneable environment coupling and disorder.

Secondly, novel quantum coherent energy transport schemes can be devised in the simple atomic system, that might then be generalisable to the more complex light-harvesting devices. The inclusion of atomic motion naturally provides adiabatic excitation and entanglement transport. Different geometries allow the creation of artificial conical intersections and transport switches [2]. We then consider whether the processes uncovered may hold relevance for real biological systems [3].

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Molecular alignment measured with photoelectron ionization yields

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We studied the rotational wavepacket evolution of linear molecules aligned by a femtosecond laser pump pulse with detection of electron photoionization yields produced by a variably delayed probe pulse. The same experimental setup was used as was previously employed for above-threshold ionization (ATI) measurements [1]. The temporal evolution of the photoelectron yields as a function of the probe pulse delay was measured for linearly or circularly polarized pump pulses, and revivals of the rotational wavepacket were observed in O_2 , CO, and C_2H_2 gases. It is shown that this new method based on detection of photoelectrons is versatile and sensitive and opens new possibilities in studies of a field-free molecular alignment in addition to common approach that uses ion yields for the detection.

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MONDAY

Investigating (*R*)-3-methylcyclopentanone Conformers using Temperature Dependent Raman Spectroscopy

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Recorded temperature dependent Raman spectra of neat (*R*)-3-methylcyclopentanone (*R*3MCP) over the Raman active C-H stretch region (2850 – 3000 cm^{-1}) are being employed to determine conformer energy difference ($\Delta H° = 4.83 \pm 0.45$ kJ/mol) between *R*3MCP equatorialand axial isomers [1]. Upon comparison with spectra obtained at room temperature, crystalline *R*3MCP Raman spectra recorded at liquid nitrogen temperature (~77 °K) are being utilized to assist identifying Raman vibrational modes rising due to *R*3MCP equatorial and axial conformers [2]. Correspondingly, DFT calculations (correlation function type B3LYP using a moderate 6-31G* and large aug-cc-pVDZ basis sets) are also manipulated to obtain highly resolved Raman spectra for the optimized geometries of equatorial and axial conformers which are also used to help identify vibrational modes rising due to each conformer [3]. Reported calculated spectra of the individual *R*3MCP conformers are shown to have good agreement with corresponding experimental Raman spectra.

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Time-sliced 3D momentum imaging of photofragmentation H_2^+

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The photofragmentation of H_2^+ was investigated with 800nm, 50fs laser pulses by employing a time-sliced 3D imaging technique that enables the measurement of all three momentum components P_X, P_Y, P_Z , which are linearly related with the pixel position and the slicing time, simultaneously for each individual product particle arriving at the detector. This allows us to measure the three-dimensional fragment momentum vector distribution without having to rely on mathematical reconstruction methods, which also require the investigated system to be cylindrically symmetric. We experimentally reconstruct the laser-induced photofragmentation of H_2^+. In most experiments, neutral molecules are used as a target, but in this work, using molecular ions, already prepared by an electric discharge, provides well-defined starting conditions and allows experiments at lower intensities.

This work was supported by the Robert A. Welch Foundation Grant No. A1546 and the Qatar Foundation under the grant NPRP 5-994-1-172.

A new method to measure photoexcitation cross-sections with a Gaussian laser beam questions the photodetachment cross-section of H^-

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A new method based on the expected behavior of the signal in the saturated regime, is described to measure photoexcitation cross-sections when a Gaussian light beam is used. The method is implemented on a negative ion beam, with a single-mode pulsed Nd:YAG laser (1064 nm), to provide the first laser measurement of the photodetachment cross-section of H^-. This cross-section is of primary importance both as the photodetachment cross-section of the most elementary negative ion and as a key parameter for the production of fast neutral H and D atoms, for plasma heating by photodetachment from accelerated ions. The obtained value 4.5(6) x 10^{-21} m^2 is greater than the one known from ancient measurements and most ab initio calculations.

Weakly bound $^{87}Rb_2(5s_{1/2}+ 5p_{1/2})1_g$ molecule: Hyperfine interaction and improved LeRoy-Bernstein analysis including nonlinear terms

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Data on $(5s_{1/2} + 5p_{1/2})$ $1_g{}^{87}Rb_2$ state under the D_1 limit, provided by a photoassociation experiment on cold atoms, have been analyzed by an improved LeRoy-Bernstein (LRB) approach including non-linear terms and provides a c_6 value of the asymptotic potential. To do that, using a model for hyperfine structure shifts, we have first subtracted the hyperfine effects observed by splitted lines and deduced the vibrational energies of each level. Then, we have compared three LRB type models to fit the data. We conclude that the next improved LRB ones is well appropriate and allows us to deduce an experimental value of c_6 (c_6=(15.14±0.05)×10^4 a.u.) [1].

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MONDAY

Observation of the $X^1\Sigma^+$ and $C^1\Sigma^+$ States of NaD Molecules

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Using pulsed optical-optical double resonance fluorescence depletion spectroscopy, the $X^1\Sigma^+$ and $C^1\Sigma^+$ states of gaseous sodium deuteride molecules have been observed and characterized. The vibrational quantum numbers of the ground $X^1\Sigma^+$ state are found from 11 to 19 by the technique of stimulated emission pumping. By comparing the theoretical calculations and utilizing the isotope-shift effect, the absolute vibrational numbering is primarily determined and the observed vibrational quantum numbers are from 10 to 57. However, the calculated potential curve of the $C^1\Sigma^+$ state shows a double-well, the rovibrational levels within the energy regime of the adiabatic double wells display irregularly in energy positions.

MONDAY

Resonance transition in atoms passing through a magnetic grating

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We study atomic spin resonance in a rubidium beam obliquely incident on a magnetic transmission grating. The atoms experience a periodic perturbation from the grating as they pass through it. The magnetic resonance transition occurs when a perturbation frequency matches the transition frequency. The magnetic grating is made by vapor-depositing magnetic material, Co-CoO, on a polyimide film, which has multiple 150- μm-wide slits separated from each other by 150 μm. This magnetic grating is relatively easy to be miniaturized, and may lead to a new type of “optics” for velocity-selective manipulation of atoms through the transition between magnetic sublevels. We have found a strong dependence of resonance spectra on whether the magnetization direction of the film is parallel or perpendicular to the surface.

Lifetime of a Spin State in an Isolated Rydberg Ion

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Forbidden transitions in metastable atomic states are useful in frequency standards and measurements of fundamental constants. Some potential applications for cosmology, atomic clocks, and quantum information are being explored in highly-ionized atoms [1]. An experimental technique has been developed recently at NIST to study forbidden transitions in multiply ionized atoms at low energy. Ions extracted from an ion source are selectively captured in a palm-sized Penning trap, isolating the charge state of interest at ~100 times lower energy within 1 ms. The radiative lifetime is measured by photon counting of spontaneous emissions from the stored ions. For the case of decay via spin-flip (M1) transition in Kr^{17+}, a relativistic Rydberg atom, various theoretical predictions are in agreement with the result of this technique at the 1% level [2]. Its transition probability has a remarkable lack of sensitivity to configuration mixing that is useful for tests of higher-order QED.

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Non-Resonant Correlation Spectroscopy in Cold Atoms: Extracting the Correlation Information of Light Sidebands

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In some of our previous work [1, 2], we have explored the noise correlation spectroscopy for laser fields under electromagnetically induced transparency condition in cold atomic ensembles. In all those studies, one of the lasers is always kept in atomic resonance and other is scanned around the resonance. We extend the analysis to the non-resonant cases of the fixed beam, coupling Zeeman transitions in $5S_{1/2}$(F=1)-$5P_{3/2}$(F`=1) of Rb^{87}. Besides the asymmetric correlation spectra, where one can switch from correlation to anti-correlation or vice-versa just by changing the laser frequency, we could get the correlation information of sidebands of the lasers. The role of analysis frequency for extracting the sidebands is highlighted as well. We observe that in the resonant case, correlation is dominated by the carriers and contribution from sidebands is suppressed. Our experimental findings are supported by a theoretical model based on conversion of phase noise to amplitude noise [3].

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Driving Rydberg-Rydberg transitions with an amplitude-modulated optical lattice

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We demonstrate a novel spectroscopic method that couples Rydberg states using an amplitude-modulated optical lattice. The method is fundamentally different from typical microwave spectroscopy: it engages the A^2-term rather than the Ap-term of the atom-field interaction Hamiltonian[1]. The method allows us to drive microwave transitions between Rydberg states with optical spatial resolution, and it is not subject to the usual electric-dipole selection rules (i.e., higher-order transitions are driven in first-order time-dependent perturbation). In the experiment, cold rubidium Rydberg atoms are excited and confined in an optical lattice of wavelength 1064nm using the ponderomotive force[2]. The $58S_{1/2}$-$59S_{1/2}$ transition is driven in first-order by modulating the intensity of the optical lattice using a tunable electro-optic fiber modulator. Maximum population transfer occurs at a lattice modulation frequency of 38.76861(1) GHz, in agreement with calculations. We display experimental results of this new lattice modulation spectroscopy.

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Towards multi-photon Raman scattering with higher excited levels of rubidium atoms in a warm ensemble

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Raman scattering in warm atomic vapors is a serious candidate for a robust light-matter interface. One possible scheme would consist of the generation of quantum information via Stokes scattering, its storage in the ground state atomic coherence and subsequent retrieval via anti-Stokes scattering.

However, intrinsic properties of atoms also lead to generation of light by many incoherent processes that cannot be spectrally separated. Our proposal is to include more levels of rubidium atom in the process, and use the diamond configuration [2,3] instead of the well-known Λ configuration. Such a system will enable us to generate quantum light at the wavelength significantly different than any Raman pump wavelength, thus greatly reducing the problem of spectral separation.

On the poster we will present theoretical results concerning four-photon Raman scattering in the diamond configuration, as well as our experiment on four-wave mixing with the abovementioned, previously undescribed, diamond configuration.

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Probe-intensity dependence of velocity-selective polarization spectroscopy at the rubidium D_2 manifold

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MONDAY

This work shows the effect of a strong, circularly polarized coupling beam on a probe beam locked to a hyperfine transition of the rubidium D_2 manifold [1]. We present experimental spectra for co- and counter-propagating beams and a rate equation calculation that does not neglect the probe beam intensity. Absorption and polarization spectra for both configurations are well reproduced by the calculation. The effect of the probe beam intensity is studied in detail in the counter-propagating configuration. Saturation and power broadening effects are observed, with different saturation intensities for each atomic line. Our analysis allows us to estimate the effective probe beam saturation intensity. In both configurations, the polarization spectra produces dispersion features ideal for locking the frequency of the coupling beam to well identified resonant frequencies. The dispersion profile slopes increase with the intensity of the probe beam, which can then control the gain of the locking device.

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MONDAY

Methods for Characterizing the Dispersion of Passive Optical Cavities using a Femtosecond Optical Frequency Comb

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Passive optical cavities are frequently used with optical frequency combs in order to perform broadband trace gas detection. However, group delay dispersion (GDD) from the cavity mirror coatings reduces the optical bandwidth that can be simultaneously coupled into the cavity. As the cavity finesse increases to improve the sensitivity of absorption measurements, this bandwidth reduction becomes more severe. For a finesse of 15000, GDD of $1fs^2$ halves the useful bandwidth transmitted through the cavity.

Characterization of the cavity dispersion is performed by scanning the relative frequencies of the comb and cavity modes whilst recording the time delay between different parts of the optical spectrum resonating with the cavity. This is achieved by dithering the cavity length[1], or the frequency offset of the comb using an acousto-optic modulator. We compare these two approaches, as well as examining the use of Optical Vernier Spectroscopy[2] to measure dispersion with higher spectral resolution.

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Coherent interactions between matter and radiation in neutral hydrogen clouds in the interstellar medium

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We investigate the possibility of coherent interactions between matter and radiation in neutral hydrogen (HI) clouds in the interstellar medium (ISM), with the goal of determining their impact on the measurement of the abundance of atomic hydrogen. Hydrogen is the most abundant species in the Universe, and the precise measurement of its density has a significant impact on our understanding of the universe. It is usually assumed that the interaction between matter and radiation is fully non-coherent in the ISM, and hydrogen abundances are calculated with this assumption. We reexamine this assumption by adapting Dicke's coherence formalism [1] to different sets of initial conditions in HI clouds in the interstellar medium and determining the intensity equation in different ensembles of atoms. We compare this intensity relation with the one calculated by the non-coherent radiation model, and discuss the order of potential corrections in the abundance measurements. In the study of coherent interactions, we have derived the Maxwell-Bloch equations for an ensemble of N hydrogen atoms interacting with the 21 cm magnetic dipole transition in the electronic ground state of the hydrogen atom. This set of equations is then solved numerically and the possibility of limited superradiance and coherence is investigated.

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MONDAY

Sensitivity improvements to the YbF electron electric dipole moment experiment

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We present a series of improvements to the preparation and detection of YbF molecules in our supersonic molecular interferometer [1]. Combined with existing improvements these will allow a ninety-fold reduction in the statistical uncertainty of our measurement of the electron's electric dipole moment (EDM), enabling us to search for an EDM below the recent upper limit of $8.9*10^{-29}$ e.cm [2]. Using laser, microwave and rf fields, we propose to pump more YbF molecules into the ground state, where they can participate in the experiment. In the detection region we plan to use techniques developed for molecular laser cooling to dramatically increase the number of scattered photons, and to use improved collection optics. Some of these techniques will also be used in the YbF fountain [3]. With this more sensitive interferometer, we will be able to continue the search for physics beyond the Standard Model.

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Improved Limit on the Electric Dipole Moment of the Electron

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The ACME collaboration has measured the electron's electric dipole moment d_e with unprecedented precision. We find d_e = (-2.1+-3.7$_{stat}$ +-2.5$_{syst}$)*10^-29 e cm [1, 2], which corresponds to an upper limit of d_e < 8.7*10^-29 e cm with 90 percent confidence. This result represents an order of magnitude improvement upon the previous best limit [3]. We describe our method of measuring d_e using a buffer gas cooled beam of thorium monoxide (ThO) and our approach to finding and quantifying systematic effects. We also discuss some of the implications of this result for fundamental physics beyond the Standard Model.

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Measuring the Electron Electric Dipole Moment with Trapped Molecular Ions

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Molecular ions in a radiofrequency trap are well-suited to measurements of the electron electric dipole moment (eEDM) due to their long coherence times. Our experiment focuses on the metastable $^3\Delta_1$ state of HfF^+, confined in a Paul trap with superimposed rotating electric and magnetic bias fields. We have measured the lifetime of this state to be 2.1(1) s, providing the ultimate limit to our possible coherence time. We have demonstrated the ability to state-selectively transfer population to the desired $^3\Delta_1$ J=1 state and to efficiently measure the population in single spin states using photodissociation. With these techniques, we performed eEDM-sensitive Ramsey spectroscopy in a rotating bias field with up to 400 ms coherence time and two counts per shot. We identify two decoherence mechanisms, bias field spatial inhomogeneity and ion-ion interactions.

MONDAY

Mercury Monohalides as Candidate Molecules for Electron Electric Dipole Moment Searches

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The possible existence of the electron electric dipole moment (eEDM) can lead to important insights into new physics beyond the Standard Model, and the matter-antimatter asymmetry of the Universe. Certain polar molecules are considered to be the best candidates for eEDM experiments, because of their large internal electric fields. The determination of the eEDM requires a combination of experimental measurements, and calculation of the molecule's internal electric field. Using relativistic many-body theory, we have established that the internal electric fields in the ground states of mercury monohalides are substantially larger than those in ThO (the molecule that leads to the current best limit on the eEDM) and YbF. In addition to their large internal electric fields, these molecules also have properties that are advantageous for experiments. This suggests that mercury monohalides are promising candidates for eEDM search experiments.

Precision Experiments with Multiply-ionized Atoms in Compact Ion Traps

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Highly charged ions have recently been isolated at low energy in compact Penning traps [1], facilitating a variety of spectroscopic studies of interest in atomic physics and metrology—such as the possibility of new atomic frequency standards [2]. One application is the study of charge-exchange (electron capture) processes using fully-stripped ions isolated at low energy. Another application involves the production and formation of low-Z, one-electron ions in high angular momentum states that are favorable for measuring fundamental constants [3]. We report on the development of a miniature electron beam ion trap (EBIT) with an attached rubidium beam oven to allow charge exchange between laser-excited Rydberg rubidium atoms and isolated bare nuclei to form one-electron ions in Rydberg states. Optical comb-based spectroscopy of such ions could provide an independent determination of the Rydberg constant [3] to help resolve the discrepancy in the proton charge radius measurements [4].

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Precision spectroscopy of atomic hydrogen for a new determination of the Rydberg constant and the proton charge radius

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The ‘proton size puzzle’ , i.e. the seven standard deviations discrepancy of the values for the proton r.m.s. charge radius extracted from hydrogen spectroscopy and elastic electron-proton scattering on the one hand and muonic hydrogen on the other hand, exists for more than three years now [1]. Still, no convincing solution to the discrepancy could be found so far. Here, we report on a new precision spectroscopy experiment, aiming to shed light on the regular hydrogen part of the puzzle: our measurement of the 2S – 4P transition frequency is the first experiment of its kind being performed on a cryogenic beam of hydrogen atoms in the 2S state [2]. We will show how this helps to efficiently suppresses leading order systematic effects of previous measurements and discuss our recent progress towards an improved determination of the Rydberg constant and the proton charge radius from high resolution spectroscopy of electronic hydrogen.

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Progress on a separated-oscillatory-field microwave measurement of the n=2 Lamb shift of atomic hydrogen

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Recent measurements of the n=2 energy separations in muonic hydrogen lead to a determination of the proton charge radius which differs from that obtained from spectroscopy in ordinary hydrogen by 7 standard deviations. We are in the process of measuring the n=2 Lamb shift of hydrogen to shed light on this discrepancy. The measurement is performed using metastable hydrogen atoms obtained from charge exchange between 50-keV protons and a neutral gas. Separated oscillatory fields are used to narrow the 100-MHz natural linewidth of the 2S-2P transition. A high signal-to-noise ratio is obtained by quenching the metastable atoms in an electric field and observing the resulting Lyman-α photons in a large-solid-angle photoionization detector.

We acknowledge funding from NSERC, CFI, CRC, ORF, and NIST.

MONDAY

Unshielded Radio-Frequency Magnetometer

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Tunable radio-frequency atomic magnetometers show promising potential as a means of detecting low-field magnetic resonance signals, for instance in substance detection by nuclear quadrupole resonance; however, previous results were obtained from magnetometers within mu-metal and radio-frequency shielding, impractical for field applications. We demonstrate a sensitivity of 0.6 $fT/Hz^{1/2}$ and a Q of 630 at 0.42 MHz without mu-metal shielding using magnetic coils and automatic shimming to compensate for earth's field. By using spatially separated magnetometers (two voxels within the same cell) as a gradiometer, sensitive to local sources, we observe interference rejection with a ratio of 1-2 orders of magnitude in a partially unshielded configuration. We are currently limited by slight mismatching of the resonance frequencies and T_2's between the two voxels, but will address how to handle this with more precise calibration and post-processing. The goal is to extend these results to a completely unshielded setting.

Experimental Test of Quantum Jarzynski Equality with a Trapped Ion

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We report on the experimental test of the quantum Jarzynski equality. The Jarzynski equality connects work done on the system to the free energy difference of the corresponding equilibrium states even through a non-equilibrium process [1]. While many experimental tests of Jarzynski equality have been performed in classical regime, the verification of the quantum version has not yet been fully demonstrated due to experimental challenges [2]. We perform the experimental test with a trapped Yb171+. We first prepare the initial thermal states of motion and we apply the laser induced force to the ion. This forces rise to the fixed maximum in different speeds ranging from quasi-static to far-from equilibrium. By projecting the initial phonon thermal state to phonon Fock state and measuring the transition probability to the different finial phonon energy states, we get the dissipated work distribution. For all these protocols, our experiment results show the Quantum equality is valid.

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Free Spin Precession as a Tool for Testing Fundamental Physics

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In the free precession of nuclear magnetic moments, any non-magnetic spin interaction will add a shift to the corresponding Zeeman splitting. In spin clocks, employing simultaneously two nuclear species, the Zeeman interaction is eliminated. This makes spin clocks a powerful tool in the search of symmetry breaking phenomena in physics. Examples of such searches include the axion particle, electric dipole moment of electron or atoms, and the Lorentz invariance violation. The sensitivity of these spin-clock based precision measurements ultimately relies on how accurate the precession frequency of the signal can be determined. There exists a statistical lower-bound in such a frequency estimation regardless of the measuring and estimating procedures adopted. We show here the evaluations of such minimum variances in case of a finite spin coherence time and compare it with our experimental data obtained by SQUID detectors.

New Experimental and Theoretical Techniques Mo-128

High-Performance Parallel Solver for 3D Time-Dependent Schrodinger Equation for Large-Scale Nanosystems

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A parallelized three-dimensional time-dependent Schrodinger equation (TDSE) solver for one electron systems is presented in this paper. The TDSE solver is based on finite-difference method in Cartesian coordinates and uses simple explicit leap-frog numerical scheme. This simplicity provides very efficient parallelization and high performance of calculations using graphical processing units (GPUs). E.g. calculation of 106 time-steps on the 1000x1000x1000 numerical grid takes only 16 hours on 16 Tesla M2090. The TDSE solver demonstrates scalability (parallel efficiency) close to 100% with some limitations on the problem size. The comparison with other TDSE solvers shows that GPU based TDSE solver is 3 times faster for the problems of the same size and the same cost of computational resources, this benefit can be increased up to 10 times using problem-specific non-Cartesian coordinates. The TDSE solver was applied to the calculation of the resonant charge transfer during H^+ - H^0 collision.

New Experimental and Theoretical Techniques Mo-129

Time of Flight Mass Spectrometer for Molecular Ion Trapping

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A time of flight mass spectrometer is implemented for a linear quadrupole trap which allows for measurement of trapped-ion reaction rates with background gasses, introduced buffer gasses, and co-trapped species. Measurements of the decay rate of SrF^+through various modes demonstrate the viability of the technique.

Coherent Stern–Gerlach momentum splitting on an atom chip

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In the Stern–Gerlach effect, a magnetic field gradient splits particles into spatially separated paths according to their spin projection. The idea of exploiting this effect for creating coherent momentum superpositions for matter-wave interferometry appeared shortly after its discovery, almost a century ago, but was judged to be far beyond practical reach. Here we demonstrate a viable version of this idea [1]. Our scheme uses pulsed magnetic field gradients, generated by currents in an atom chip wire, and radio-frequency Rabi transitions between Zeeman sublevels. We transform an atomic Bose–Einstein condensate into a superposition of spatially separated propagating wavepackets and observe spatial interference fringes with a measurable phase repeatability. The method is versatile in its range of momentum transfer and the different available splitting geometries. These features make our method a good candidate for supporting a variety of future applications and fundamental studies.

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Phase space tomography using an atom chip with random and engineered fragmentation potentials

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We demonstrate tomographic reconstruction of the phase space distribution of atoms oscillating in a harmonic trap with weak potential corrugation caused by nano-scale imperfections in an atom chip wire [1]. Deformations of these distributions – explained in terms of angular velocity dispersion of iso-energetic phase space trajectories – are highly sensitive to anharmonic components of the potential. This method may be important for characterizing future devices based on trapping and guiding atoms.

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Injection locking of a high power ultraviolet laser diode for laser cooling of ytterbium atoms

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We have developed a high-power light source at 399nm for laser cooling of ytterbium atoms with an ultraviolet laser diode by using injection-locking. So far, the output power of a laser diode system was limited to 80mW[1] for this wavelength. We implemented an injection-locking system of a high power laser diode (NICHIA NDV4B16) and obtained 220mW of output power.

The output wavelength of the slave laser diode was originally centered at 402nm and was shifted to 399nm by decreasing the chip temperature to -16 degrees. In order to avoid condensation, the box was purged with nitrogen gas. 5mW of master laser source was prepared by using a frequency-doubled CW Ti:S laser. This light source can be used for Zeeman slowing, magneto-optical trapping[2], and transverse two-dimensional cooling of ytterbium atoms[3]. In the poster, we will present the systematic method for aligning the injection-locking using a Fabry-Perot interferometer.

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A deterministic laser-cooled source of single Si ions for solid state qubits

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An all solid state, scalable quantum computer architecture proposed by Kane[1] utilizes P dopants in Si as qubits. The major difficulty is the placement of a single qubit with nanometer precision. Laser cooling and trapping a single atom, followed by resonant photo-ionization at threshold, provides a deterministic source of a single ion which may be deposited at low energy to meet the stringent spatial demands.[2] There is no cw laser for direct manipulation of P. However, ^{31}Si beta decays to ^{31}P, and has a cooling wavelength at 221.74 nm which is achievable with a frequency quadrupled Ti:Sapphire laser.[3] In our laboratory the cooling and repump lasers, Si atomic beam with a novel Zeeman slower[4], Te_2 and I_2 frequency references and optics to detect fluorescence from single atoms for a magneto-optic trap have been developed and investigated. Progress of this research will be reported.

Work supported by the W.M. Keck Foundation.

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Room-Temperature Microwave Saturation Spectroscopy of Nitrogen-Vacancy Ensembles in Diamond

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The nitrogen-vacancy (NV) color center in diamond has generated much recent interest for use in quantum information and sensing. The NV ground-state microwave transitions suffer from inhomogeneous broadening, which limits the achievable sensitivity and coherence time, especially in high-density NV ensembles. To better understand and remove the sources of broadening, we performed saturation spectroscopy of the NV microwave transitions. We show that the inhomogeneous broadening comes primarily from differences in magnetic field from nearby spins, and we demonstrate that saturation spectroscopy is useful for magnetic-field-insensitive NV thermometry.

MONDAY

Diamond Magnetometry of Superconducting Thin Films

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In recent years diamond magnetometers based on the nitrogen-vacancy (NV) center have been of considerable interest for applications at the nanoscale. An interesting application which is well suited for NV centers is the study of nanoscale magnetic phenomena in superconducting materials. We employ NV centers to interrogate magnetic properties of a thin-layer yttrium barium copper oxide (YBCO) superconductor [1]. Using fluorescence-microscopy methods and samples integrated with an NV sensor on a microchip, we measure the phase transition temperature and the penetration field of vortices, and observe pinning of the vortices in the layer. These measurements are done with a 10 nm thick NV layer, so that high spatial resolution may be enabled in the future. Based on these results, we anticipate that this magnetometer could be useful for imaging the structure and dynamics of vortices with the hope of contributing new experimental insight to the open question of high Tc superconductors.

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A single frequency tunable laser near 1000 nm for spectroscopic applications

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We have built a tunable single frequency laser using the master oscillator power amplifier (MOPA) configuration. The laser has an output power over 1 W in the spectral range from 990 nm to 1030 nm. For further applications, the laser will be used to study the optogalvanic spectroscopy of the atomic neon and Doppler-free two-photon spectroscopy of the He $2^1S_0 \rightarrow 3^1D_2$ transition as well as used to excite atomic potassium from the ground state 4S through the 5P state to the highly lying Rydberg state nS (n > 20) for studying the ultracold potassium Rydberg atoms.

ATOMIC CLOCKS

Hyperfine structure in $^{229g}Th^{3+}$ as a probe of the $^{229g}Th \to ^{229m}Th$ nuclear excitation energy

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We describe a potential means to extract the $^{229g}Th \to ^{229m}Th$ nuclear excitation energy from precision microwave spectroscopy of the $5F_{5/2,7/2}$ hyperfine manifolds in the ion $^{229g}Th^{3+}$. The hyperfine interaction mixes this ground fine structure doublet with states of the nuclear isomer, introducing small but observable shifts to the hyperfine sub-levels. We anticipate that accurate atomic structure calculations may be combined with measurements of the hyperfine intervals to quantify the effects of this mixing. Further knowledge of the magnetic dipole decay rate of the isomer, as recently reported, allows an indirect determination of the nuclear excitation energy.

A search for ultra-low energy nuclear isomer state of Thorium-229 -- New method using synchrotron radiation X-ray source--

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Thorium-229 has been known for its extreme low energy isomer state. The recent indirect measurement of the energy level (~7.8 eV) implied that it could be excited with laser light and many experimental techniques related to atomic- and molecular-physics could be adapted. Since the nucleus is shielded by core electrons and relatively insulated from the influence of its external field, it attracts a lot of interest from many fields, e.g. atomic clock, fundamental physics, and etc. However, no direct evidence of excitation/de-excitation signal of thorium-229 isomer state was achieved so far.

Aiming to adopt this system as a target system for neutrino mass spectroscopy, we proposed to search for the isomer state directly using intense X-ray source. In this conference, we will describe the new search method and report recent result of the pilot experiment using naturally abundant thorium-232 at spring-8, synchrotron radiation facility.

Towards a measurement of the nuclear isomer transition in Thorium-229

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The ^{229}Th nucleus is unique as it possesses an extremely low-lying isomer state. Its energy is expected to be about 7.8 eV [1], corresponding to a transition into the nuclear ground state of 160 nm. This transition has been proposed for a nuclear clock, which would be largely immune against perturbations of the environment [2]. The transition frequency might be highly sensitive to drifts in fundamental constants. A direct evidence of this transition, however, is still pending.

We follow two approaches to confirm the existence of the isomer state and determine its energy. The first approach employs a magnetic micro-calorimeter with supreme resolution. We record the spectrum of gamma photons originating from the decay of excited nuclear states, aiming to resolve the ground state doublet structure.

In a second approach, we directly excite the isomer transition using VUV light around 160nm. The ^{229}Th atoms are embedded into a VUV-transparent CaF_2 host crystal, and we measure its fluorescence as the laser is scanned across the resonance.

We report on the current status of these experiments.

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Search for optical excitation of the low-energy nuclear isomer of Th-229

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Direct optical excitation of the nuclear transition between the ground state and the 7.8 eV isomer in Th-229 is the missing link towards a study of this system as a precise nuclear clock. We plan to use two-photon laser excitation via electronic bridge processes in Th^{+} [1]. In resonant two-step laser excitation of trapped Th^{+} ions, we observe 43 previously unknown electronic energy levels within the energy range from 7.3 to 8.3 eV [2,3]. The high density of states promises a strongly enhanced nuclear excitation rate. Using laser ablation loading of the ion trap and photodissociation of molecular ions that are formed in reactions of Th^{+} with impurities in the buffer gas, we now efficiently load and stably store ions of the radioactive Th-229 isotope. We have measured the hyperfine structure of the 402 nm resonance line and have started a search for the nuclear resonance over the presently wide wavelength uncertainty range.

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MONDAY

^{229}Th and ^{232}Th Optical Spectroscopy System for Nuclear Frequency Standard

Andrey Krasavin[1], Victor Troyan[1], Petr Borisyuk[1], Vitaly Palchikov[1, 2], Alexey Sysoev[1], Sergey Poteshin[1], Dmitry Chernyshev[1], Valery Yakovlev[1]

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The results are presented on comparison of different techniques of producing thorium ions: from solid $Th(NO_3)_4$ and ThO_2 compounds by laser ablation, from nitrate solution of ^{229}Th and ^{232}Th by inductively coupled plasma mass-spectrometry, and also from metallic thorium by electron-beam evaporation.

The electron-beam evaporation technique provides a basis for the high-resolution optical spectroscopy system developed at MEPhI, Moscow. This system allows performing the following tasks:

to form a mass selective beam of singly and triply charged $^{229}Th^{n+}$ and $^{232}Th^{n+}$ ions with mass resolution better than 1 amu;

to capture and hold multiply charged $^{229}Th^{n+}$ and $^{232}Th^{n+}$ ions coming from the mass selective ion source with energy between 1 to 500 eV, in RF quadrupole linear ion trap;

to cool trapped $^{229}Th^{n+}$ and $^{232}Th^{n+}$ ions in buffer gas atmosphere to room temperature;

to proceed to high-precision research on optical and nuclear isomeric emission and absorption spectra of ^{229}Th isotope.

Improving atomic clocks using coherence preserving measurements

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Atomic clocks have reached stabilities at the 10^{-18} level thanks to a tremendous progress in the development of ultra-stable optical local oscillators (LOs). Nevertheless, the decoherence source represented by noise of the local oscillator still limits the clock stability. We want to remove this limitation using coherence preserving measurements of the atom-LO phase, to achieve longer effective interrogation times. We implemented a non-destructive frequency modulation detection for the measurement of the number difference on the ^{87}Rb clock transition. With this probe we could observe the real time evolution of a collective spin and correct it using feedback [1].

References

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Development of an ultra-stable universal synthesiser for state-of-the-art frequency metrology

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Technical details and evaluation results will be presented from a new femtosecond comb system being developed at NPL to act as a 'universal synthesiser' for high accuracy frequency metrology. This concept allows multiple frequency standards to benefit from the stability of a single 'master oscillator', currently a Nd:YAG laser stabilised to a 30 cm-long ULE cavity with fused silica mirrors and projected thermal noise of 1×10^{-16}. A multi-branch fibre comb simultaneously transfers the stability of the master oscillator to the microwave domain and to several optical frequencies. The microwave signal will be used for interrogation of the NPL Cs fountains, promising quantum projection noise limited performance. The optical frequencies, designed for 10^{-16} level stability at 1 s, correspond to clock transitions in the Yb^+, Sr^+ and Sr optical frequency standards at NPL. A 1.5 µm branch also allows remote comparison of these standards with those in other laboratories over telecom fibres.

Towards Optical Clocks and Coherent Frequency Transfer in Sweden

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Within SPs commitment as a National Metrology Institute (NMI), a program towards optical clocks and coherent frequency transfer are being initialized. With the aid from Swedish Post and Telecom Authority (PTS), we have recently been able to equip a new laboratory with an optical frequency comb and an ultra-stable laser from Menlo Systems.

With this equipment as a foundation, SP are now working towards an optical lattice clock based on strontium atoms. The system will be built with the aim of being robust and easy to upgrade. The hope is that the system will be a future Swedish frequency reference and a source for frequency transfer over optical fiber. Even without a fully operational clock, the ultra-stable laser will allow for testing frequency transfer methods way below the 10^{-13} level.

The poster will present the research program in more detail, the current status, and our future plans within the field.

TACC - Trapped Atom Clock on a Chip

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Trapped atoms have grown in importance for atomic clocks and atom interferometers. Besides optical lattice clocks, devices for in-the-field application benefit from the reduced volume combined with high sensitivity. Here, chip-scale devices are particularly appealing. Operating a clock with ^{87}Rb trapped on a microchip [1], we evaluate the performance of such systems under metrology conditions. At ultra-low temperatures, we have observed spin self-rephasing and 58s coherence time [2]. Spectroscopy has revealed the underlying energy gap between pair-wise singlet and triplet states due to s-wave interaction [3].

Here we present the clock stability of 6 10^{-13} at 1s and 6 10^{-15} at 30 000s. The absolute clock frequency shows an evolution with Ramsey time, which we model using the spin self-rephasing mechanism. We identify a range of parameters presenting particular advantages to the clock operation. Our findings apply to any trapped atom sensor and may impact quantum information processing.

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Compact Frequency Standard with Cold Atoms: Transportable System

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The theoretical and experimental knowledge acquired with other standards are now employed in the development of a mobile atomic frequency standard based on cold sample of cesium atoms.

The basic principles shown previously allow us to build a new model of atomic clock with the cold cloud expanding inside a cylindrical microwave cavity. The operation of this experiment is different from conventional cold atoms fountains, since all the steps are sequentially performed in the same place. In addition to this main characteristic, this new model is suitably compact to allow several applications, where all the essential parts are being coupled in a single metal block. All these parts (cavity, lasers, microwave chain, vacuum chamber and control system) require mechanical and electrical stability, and an efficient vacuum. The metal block addition to provide mechanical stability to the system will also obtain the thermal stability necessary for the microwave cavity and lasers.

References

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Decoherence time of Ramsey fringes observed in a cesium atomic fountain clock

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The Ramsey fringes of the cesium atomic fountain clock NMIJ-F2 were analyzed rigorously as a function of the interefence time from 0.1 s to 0.7 s, which was adjusted by changing the velocity of the launched atoms. The obtained fringes were fitted by the function of the theoretical Ramsey fringes with a velocity spread. The analytical results showed that the temperature spread of the vertical direction was 1.7 μK, which corresponds to the value obtained from the measurement of time-of-flight. The visibilities of fringes as a function of the interaction times were well fitted by a function of $V(t)=V(0)\exp[-g(t)t]$, where $g(t)$ is the decay rate that is proportional to an atom density. The corrected decoherence time was obtained to be t_d =56 s. Such a long time will indicate that the quantization scale of gravity is longer than $3200L_P$ m where L_P is Plank length.