Mott Insulator to Superfluid transition in Bose-Bose mixtures in a two-dimensional lattice

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We perform a numeric study (Worm algorithm Monte Carlo simulations) of ultracold two-component bosons in two-dimensional optical lattices. We study how the Mott insulator to superfluid transition is affected by the presence of a second superfluid bosonic species. We find that, at fixed interspecies interaction, the upper and lower boundaries of the Mott lobe are differently modified. The lower boundary is strongly renormalized even for relatively low filling factor of the second component and moderate (interspecies) interaction. The upper boundary, instead, is affected only for large enough filling of the second component. Whereas boundaries are renormalized we find evidence of polaron-like excitations. Our results are of interest for current experimental setups.

Quantum interface between frequency-uncorrelated down-converted entanglement and atomic-ensemble quantum memory

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Photonic entanglement source and quantum memory are two basic building blocks of linear-optical quantum computation and long-distance quantum communication. In the past decades, intensive researches have been carried out, and remarkable progress, particularly based on the spontaneous parametric down-converted (SPDC) entanglement source and atomic ensembles has been achieved. Currently, an important task towards scalable quantum information processing (QIP) is to efficiently write and read entanglement generated from a SPDC source into and out of an atomic quantum memory. Here we report the first experimental realization of a quantum interface by building a 5 MHz frequency-uncorrelated SPDC source and reversibly mapping the generated entangled photons into and out of a remote optically thick cold atomic memory using electromagnetically induced transparency. The frequency correlation between the entangled photons is almost fully eliminated with a suitable pump pulse. The storage of a triggered single photon with arbitrary polarization is shown to reach an average fidelity of 92% for 200 ns storage time. Moreover, polarization-entangled photon pairs are prepared, and one of photons is stored in the atomic memory while the other keeps flying. The CHSH Bells inequality is measured and violation is clearly observed for storage time up to 1 . This demonstrates the entanglement is stored and survives during the storage. Our work establishes a crucial element to implement scalable all-optical QIP, and thus presents a substantial progress in quantum information science.

Calculations of electron tunneling between atomic particle and metal surface

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A numerical simulator has been developed for efficient calculation of resonant electron exchange (tunneling) between an atomic particles (ions and single atoms) and metal surface. The numerical model was based on Anderson-Newns Hamiltonian and wide zone approximation. Conduction band of metal surface was described as a limited set of discrete (energy) levels. The core of calculation scheme is decomposition of atomic wave function on basis of eigen wave functions and further solution of system of time-dependent equations for decomposition coefficients. The character of time-dependence of the electron tunneling has been investigated by means of described model. In particular the influence of ratio atomic-level-width/conduction-band-width has been studied. It was found, that in the case of "thin" atomic level (atomic level width is much smaller than conduction band width) an exponential decay of atomic level takes place. The DOS (density of electron states) in this case has a Lorentzian form. In the case of "thick" atomic level (atomic level width is comparable with conduction band width) an electron oscillations occurs, which means that electron transfers from atom to surface and back. I.e. population of atomic level oscillates in time. The extra-states in DOS appear in this case. The presented model could be used for calculation of electron exchange during ion scattering and secondary ion emission, and for fast approximation of DOS in metallic surface's conduction band. The author gratefully acknowledge the financial support provided by the Russian Foundation for Basic Research (Grant 10-02-00162-a) and the grant of the President of the Russian Federation for support of young scientists (MK-1139.2009.2).

Spin Squeezing in Broadband Atomic Magnetometry

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We demonstrate sub-projection-noise (PN) sensitivity and spin squeezing in a broadband atomic magnetometer using quantum non-demolition (QND) spin measurements. A cold, dipole-trapped sample of ^{87}Rb atoms is probed by paramagnetic Faraday rotation[1]. We calibrate the apparatus using a known reference state, the maximum-entropy or thermal spin state (TSS)[2], and probe using a dynamical decoupling technique[3]. We measure a sensitivity 2.8 dB better than the spin noise for the TSS (1.6 dB better than the PN of a coherent spin state) with 7.6×10^5 atoms. We demonstrate spin squeezing of a magnetically sensitive coherent spin state prepared in the F=1 hyperfine manifold with a spin noise reduction by 2.9 dB compared to the initial PN. The measurement induced depolarisation of the state is 10 %, giving a 2 dB metrological gain.

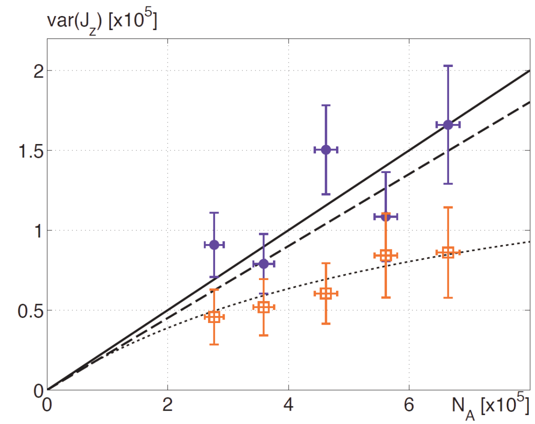

Figure 1: *Variance (dots) and conditional variance (squares) of $\hat{J}_z$ for different atom numbers N_A. Errorbars indicate the statistical uncertainties of calculated variances. The solid black line is the calculated PN from the independently measured coupling strength for the QND interaction. The dotted (dashed) line is the simulated spin noise reduction for no (20%) detection loss[4].*

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Degenerate Bose-Fermi Gases in Microgravity

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Bose-Einstein Condensates (BEC) opened the way for realization of atomic ensembles with Heisenberg limited uncertainty. In microgravity extremely dilute samples of BEC can be obtained and observed after a free evolution on time scales of seconds. Applications range from condensed matter physics to ultra high precision measurements. This has led us to realize ^{87}Rb BECs of $\sim 10^4$ atoms in microgravity created during the free fall of our experiment. The experimental results (to be published) establish the fact, that in a microgravity environment ultra-large condensates (1.5 mm) can be observed after a free evolution of 1 second. Our second generation experiment being set up right now uses ^{87}Rb and ^{40}K as degenerate Bose and Fermi gases respectively. It can be used to carry out experiments on Bose-Fermi mixtures, interferometry and tests of the equivalence principle in the quantum domain. Further more, it will greatly benefit from a mass independent confining potential naturally available in the microgravity environment. An up to date progress of our activities and future prospects will be presented.

Phase-Sensitive Amplification by Four-Wave Mixing in an Atomic Vapor

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A phase-sensitive amplifier (PSA) is based on a parametric process that can amplify or deamplify a signal depending on the phase of the input. It does so without degrading the signal to noise ratio of the input, contrary to a phase-insensitive amplifier (PIA) which adds at least 3dB of noise to the signal in the limit of high gain. This makes it possible to obtain noiseless amplification of a signal, making it a key element in optical communication systems. For the particular case where the input signals phase is chosen for maximum deamplification the PSA can generate squeezed light.

We present an experimental realization of a phase-sensitive optical amplifier using a four-wave mixing interaction based on a double-lambda configuration in hot Rb vapor. We report nearly noiseless amplification for a range of gains as well as the generation of single-beam squeezing. We compare the results obtained with a theoretical phase-insensitive scheme. The lack of a cavity in our system and relaxed phase-matching conditions can be used to observe noiseless amplification of multi-spatial-mode signals (i.e. images).

K-shell photodetachment from O^- *

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The K-shell photodetachment spectrum of O^- has been investigated using the merged ion-photon beam photodetachment technique. O^- ions were produced in a Cs sputtered negative ion source (SNICS II) on a new Movable Ion Photon Beamline (MIPB) while the photons were produced by the undulator on the Advanced Light Source Beamline 8.0.1. Positive oxygen ions formed by multiple detachment were detected as a function of photon energy. Photoexcitation of a 1s electron leads to a short-lived Feshbach resonance due to the extra stability of the now full $2p^6$, shell. [5] The Feshbach resonance is observed near 525 eV in the O^+, O^{2+} and O^{3+} channels. About 3 eV above the narrow resonance, a p-wave detachment threshold is observed. Comparisons to inner-shell photoionization of O will be discussed for both experiment [6] and theory. [7]

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Phases of a 2D Bose Gas in an Optical Lattice

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Ultra-cold atoms in optical lattices realize simple, fundamental models in condensed matter physics. We create an ensemble of about 60 harmonically trapped 2D Bose-Hubbard systems from a ^{87}Rb Bose-Einstein condensate in an optical lattice and use a magnetic resonance imaging approach to select a few 2D systems for study, thereby eliminating ensemble averaging. Our identification of the transition from superfluid to Mott insulator, as a function of both atom density and lattice depth, is in excellent agreement with a universal state diagram[8] suitable for our trapped system. In agreement with theory, our data suggests a failure of the local density approximation in the transition region.

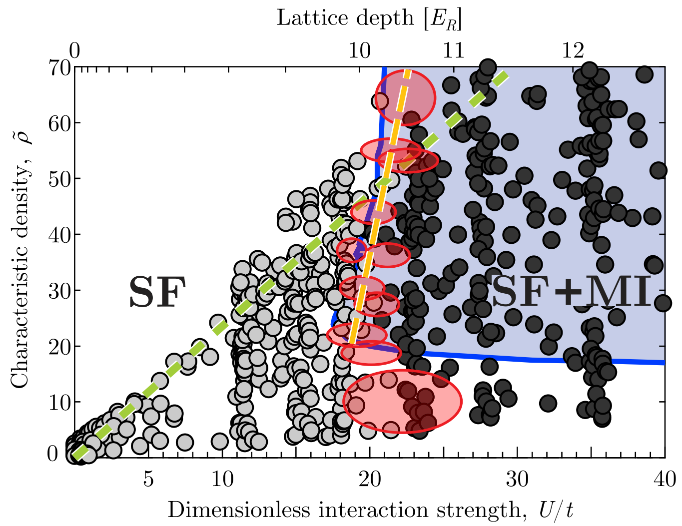

Figure 1: *State diagram for a harmonically trapped 2D Bose gas*[9].

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Multi-Photon Laser Cooling

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We explore laser cooling and trapping that includes light forces from transitions between electronically *excited* states in a Cs magneto-optical trap (MOT) [10]. We demonstrate a particular MOT geometry where all cooling and trapping along one direction are due to optical forces arising from excited-to-excited transitions. We observe efficient trapping and sub-Doppler temperatures. This approach may have applications in background-free detection of trapped atoms, and in assisting cooling of certain atomic or molecular species that require lasers at inconvenient wavelengths. In this context, we briefly discuss a proposal to cool hydrogen or anti-hydrogen atoms using excited-to-excited state transitions.

Starting with a standard Cs MOT configuration operating on the cycling transition between the ground $6S_{1/2}$ and excited $6P_{3/2}$ states (labeled g and e respectively), we replace the pair of g-e laser beams along the z direction with counter-propagating beams that only couple the $6P_{3/2}$ to the further excited $8S_{1/2}$ states (labeled e'). In this configuration, all cooling and trapping along the z direction are due to the e-e' laser light.

With the e-e' beams at moderate intensity ($2\Omega_{ee'}^2/\gamma^2 \simeq 15$, for Rabi frequency $\Omega_{ee'}/2\pi$ = 4MHz and an e' inverse linewidth γ), we find a stable two-color MOT for small negative 2-photon detunings δ_2. The optimal e-e' beam helicities are opposite to those for a standard MOT. The cloud size and effective temperatures are anisotropic, and can be understood in terms of a 2-photon Doppler cooling picture

At higher intensities, ($2\Omega_{ee'}^2/\gamma^2 > 80$) we observe two remarkable behaviors: the MOT works over a wide range of two-photon detunings, including on the blue detuned side, and the measured temperatures are sub-Doppler along all directions, even relative to the narrow $8S$ linewidth. The 2-photon Doppler cooling picture fails, and we use a 3-photon picture, where 2-photon absorption to $8S$ is followed by Doppler-sensitive stimulated emission back to the $6P$ state. The stimulated emission can effectively adiabatically eliminate the $8S$ state either at red or blue detuning. The sub-Doppler cooling involves polarization and intensity gradients of multi-photon processes. We have developed a semi-classical model and performed numerical simulations that show sub-Doppler behavior, consistent with the experimental results.

The success of this scheme might be applicable to other species. For example, we have developed a related scheme to cool hydrogen, and propose that efficient Sisyphus cooling of hydrogen atoms on the $2S$-$3P$ Balmer line should be possible, following excitation to the $2S$ level.

[10] S. Wu, T. Plisson, R. C. Brown, W.D. Phillips and J. V. Porto, *Phys. Rev. Lett.* **103** 173003 (2009).

Density fluctuations in degenerate Fermi gases

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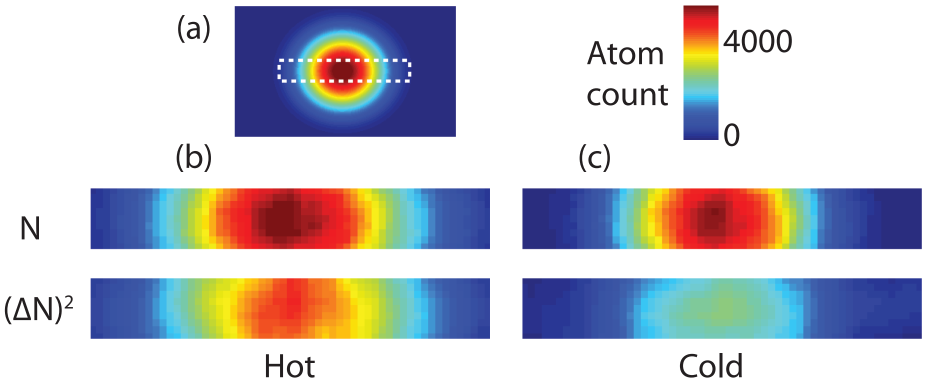
We study density fluctuations in degenerate Fermi gases at different interaction strengths. For an ideal, noninteracting Fermi gas we observe Pauli suppression of density fluctuations (atom shot noise) for cold clouds deep in the quantum degenerate regime. Strong suppression is observed for probe volumes containing more than 10,000 atoms. Measuring the level of suppression provides sensitive thermometry at low temperatures. For a strongly interacting spin mixture through the BEC-BCS crossover, we use dispersive imaging to measure the relative density fluctuations between the two spin states. For a sample composed of molecules or of generalized Cooper pairs, we observe that the relative density fluctuations are strongly suppressed, while the fluctuations in total density increase or remain the same. This method constitutes a direct measurement of pairing that does not rely on magnetic field ramps or the interpretation of RF spectra, and should be useful in identifying interesting phases in a variety of systems, including itinerant ferromagnetism and the Mott insulating and antiferromganetic phases in optical lattices.



Engineering Dissipation in Quantum Systems

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Much of the laser cooling techniques used in cold atom systems rely on a presence of the dissipative channel to remove entropy from the system. However, dissipative cooling typically leads to decoherence of qubits - the bane of quantum computing. The proposed research will focus on techniques to decouple the dissipative channel from the qubit states and allow for coherent cooling of neutral atom qubits. This problem will be attacked on two fronts:

- Nuclear spin preserving sideband cooling in ^{171}Yb, which can take place by decoupling the electronic and nuclear spins.
- Cooling of Ytterbium in an optical lattice by means of a Rubidium BEC. This approach will proceed along the lines of Raman cooling replacing the spontaneously emmited photon by a phonon excitation in the BEC. The low temperature of the BEC makes it a phonon vacuum which can absorb entropy and energy from the lattice, thus cooling the lattice.

We describe techniques that will be used to craft robust dissipative channels that not only allow for coherent cooling of qubits, but also permit us to reach temperatures well below currently attainable limits. Furthermore, the ability to create ultracold mixtures of Rubidium and Ytterbium should open the possibility to study Bose-Fermi mixtures in optical lattices.

Simulation of Quantum Magnets

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The magnetic order of interacting quantum spins is of fundamental interest in many areas of physics, and it is related to several exotic material phenomena, such as magnetic frustration, spin liquids, and high-Tc superconductivity. Theoretical studies on those phenomena would demand a quantum computer, because quantum superposition and entanglement make a many-body system classically intractable. Trapped ion systems have been identified as a promising physical implementation of a quantum simulator, thanks to the strong and tunable couplings between ions and its advanced status on quantum computation applications. In this poster we will present our most recent results of quantum simulations of frustrated Ising spins utilizing a system of trapped atomic ions. We polarize the spins along a transverse effective magnetic field and adiabatically turn on the Ising couplings and directly observe the ground state spin configurations. This system is scalable to a larger number of spins, in a regime where the classical simulations cannot be performed.