Workshop on

Quantum Simulations with Ultracold Atoms

(Trieste, 16-20 July 2012)

POSTER SESSION

(19 July, 18,30)

Behavior of a radiation-matter system under dynamical crossing of a quantum phase transition

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We numerically study the dynamical response of a finite set of two level systems symmetrically coupled to a radiation field confined in a cavity, thus constituting a finite-size Dicke Model. This model presents a Quantum Phase Transition in the thermodynamic limit across a definite set of its parameters. Unlike previous works, which focused on static properties of the phases of the system, we will study the dynamical crossing of the phase boundary. We will focus on transitions between instantaneous eigenstates and excess energy. For a certain evolution regime, there is an excellent agreement with the sudden quench approximation, and then a size-proportional universal scaling is present. On the other hand, as the adiabatic regime is approached, very different regularities are present.

Dilute Bose gas in quasi-2D correlated random potentials

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Laser speckles provide a unique possibility to create fully controlled two-dimentional disorder potentials for neutral atoms. This type of disorder has exponential probability distribution and finite spatial orrelation length. In this talk, I shall present our resent results on the superfluidity and Bose-Einstein condensation of interacting bosons in the presence of the laser speckles at zero temperature obtained using Monte Carlo methods in continuum as well as Gross-Pitaevskii equation and Bogoliubov theory.

Theory of polarons, molecules and RF-spectra in a quasi-2D Fermi gas

Stefan K. Baur and Jesper Levinsen

We study the effects of the quasi-two dimensional nature of experiments with ultra-cold Fermi gases. These effects manifest in the energetics of polaron and molecular states of impurities in an ultra-cold Fermi gas and, as we show, they also display profound effects on radio-frequency spectra through final state interactions.

Graphene qubits and their application to quantum simulation of photosysnthetic complexes

Colin Benjamin

Qubits or quantum bits are the nuts and bolts of a quantum computer. In this context superconducting qubits are more prized as they can be easily integrated into current technology. Controlling them hitherto has been a challenge. In the solidstate their control is mainly via magnetic fields. At low dimensions in which they operate however this type of control is most challenging. The talk will introduce the idea of controlling superconducting qubits, built from the wonder material called graphene, via a gate voltage alone obviating the need for external magnetic fields. We will apply this to simulating a photosynthetic complex much in vogue nowadays because of the tantalizing prospect of quantum coherence being observed therein.

Ultracold atoms in non-Abelian gauge potentials preserving the Landau levels

M. Burrello

Recent experiments proved that is possible to simulate both an artificial magnetic field and a spin-orbit coupling in ultracold atomic gases, opening the way to obtain effective non-Abelian gauge potentials. Here we study ultracold atoms subjected to U(2) non-Abelian potentials that preserve the analytic structure of the Landau levels, which is necessary for the appearance of fractional quantum Hall states. These gauge potentials deform the Landau levels and split, in general, their pseudospin degeneracy, which is recovered only in particular points. The introduction of intraspecies and interspecies interactions brings to the presence of fractional quantum Hall states that can be analitically described far from and at the degeneracy points for both fermions and bosons. The Haldane pseudopotentials for the deformed Landau levels provide a useful tool to investigate the role of the interactions in the appearance of both Abelian and non-Abelian fractional quantum Hall states.

The Contact in the BCS-BEC crossover for finite range interacting ultracold Fermi gases

Santiago F. Caballero-Benítez, Rosario Paredes and Víctor Romero-Rochín

Using mean-field theory for the Bardeen-Cooper-Schriefer (BCS) to the Bose-Einstein condensate (BEC) crossover we investigate the ground state thermodynamic properties of an interacting homogeneous Fermi gas. The interatomic interactions modeled through a finite range potential allows us to explore the entire region from weak to strong interacting regimes with no approximations. To exhibit the thermodynamic behavior as a function of the potential parameters in the whole crossover region, we concentrate in studying the contact variable, the thermodynamic conjugate of the inverse of the s-wave scattering length. Our analysis allows us to validate the mean-field approach across the whole crossover. It also leads to predict a quantum transition-like in the case when the potential range becomes large. This finding is a direct consequence of the k-dependent energy gap for finite interaction range potentials.

Polar bosons in one-dimensional disordered optical lattices

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We analyze the effects of disorder and quasi-disorder on the ground-state properties of ultra-cold polar bosons in optical lattices. We show that the interplay between disorder and inter-site interactions leads to rich phase diagrams. A uniform disorder leads to a Haldane-insulator phase with finite parity order, whereas the densitywave phase becomes a Bose-glass at very weak disorder. For quasi-disorder, the Haldane insulator connects with a gapped generalized incommesurate density wave without an intermediate critical region.

Many-body physics of Rydberg-dressed Atoms

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We present an exhaustive study concerning two-dimensional Bose-Einstein-condensated systems, in which atoms are dressed to a highly excited Rydberg state [1]. Recently it has been shown that such effective interactions lead a transition to a mesoscopic supersolid state [2,3]. This enigmatic phase of matter emerges when both crystalline long-range order and off-diagonal long-range order are simultaneously observed [4].
Making use of Quantum Monte Carlo simulations, we investigated ground state properties, finite temperature phase diagrams, and incommensurability effects of supersolid phase both in the bulk limit and considering harmonic trapped systems; with the purpose to provide practical information for the observation of such an intriguing state in possible future experiments [5].
We have also scrutinised the Gross-Pitaevskii equation with a non-local interaction term, showing that one can quantitatively reproduce the superfluid-supersolid transition at finite interaction strength in agreement with Quantum Monte Carlo results at T=0 [6,7]. In addition, in the limit of rapid condensate rotations the mean field approach reveals interesting new phases coming from the competition between the supersolid crystal structure and vortex lattices [6].
Finally the validity of the mean-field analysis was verified perturbing the ground state wave function and looking at the spectrum of the corresponding Bogoliubov equations [7]. This approach provides an intuitive physical insight to the low energy dynamics of the system and is validated through the comparison of our findings with recent Monte Carlo simulations [8].

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Pairing and Mott instabilities of 1D and quasi-1D dipolar gases

Marcello Dalmonte

Recent developments in cooling and controlling ultracold gases of magnetic atoms and polar molecules open a new perspective on many-body physics of ultracold gases, which was previously strongly related to contact interactions. We will present a theoretical analysis of bosonic and fermionic gases confined in 1D and quasi-1D geometries, combining analytical approaches based on the Tomonaga-Luttinger liquid formalism with numerical DMRG calculations. Several phenomena are investigated, from the formation of a staircase of insulating phases to the emergence of exotic pairing instabilities which are stable even in standard experimental setups.

Counterflow superfluid in one-dimensional Bose-Fermi mixtures in optical lattices

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Motivated by the recent realization of mixed Mott insulators of 174 Yb-173 Yb mixtures [1], we study the quantum phases of one-dimensional Bose-Fermi mixtures in optical lattices and focus on the case of repulsive interparticle interactions, equal mass, and unit total filling [2]. Using both Tomonaga-Luttinger liquid theory and time-evolving block decimation method, we calculate the ground state phase diagrams as functions of the interparticle interactions, the hopping, and the population imbalance. We find that a counterflow superfluid phase with triplet pairing of polarons, which are composite particles consisting of a fermion and bosonic hole, occupies a broad range of the parameter space. We suggest that the counterflow superfluid order emerges in the mixed Mott insulators of 174 Yb-173 Yb mixtures at low temperatures.

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A diffusion Monte Carlo study of Spin-Polarized Fermionic systems

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We perform a quantum Monte Carlo simulation (based on Generalized Feynman-Kac path integral method) of strongly interacting fermions confined in a three dimensional harmonic potential. The theoretical investigation on the calculation of the density profile of a spin polarzed Fermi gas has been motivated by the experimental effort at MIT and RICE University on the fate of a BCS found state for a spin imbalanced Fermi system. Even though both groups found phase separation and no sign of FFLO, they differed for the other outcomes. For example the critical polarization is vastly different for them. MIT group found a third partially polarized phase in addition to a superfluid phase and a normal phase which is absent in the case of Rice experiment. In our work the ground state energies are calculated for a small system of Li^6 atoms interacting with an attractive potential. At this point our energies are in excellent agreement with the previous calculations and we believe that our path integral method will also help in exploring the bulk behavior of such fermionic system as a function of number of atoms and provide a benchmark for other theoretical methods.

Cavity optomechanics with a Bose-Einstein condensate

Gabriele De Chiara

We consider a cavity with a vibrating end mirror and coupled to a Bose-Einstein condensate. The cavity field mediates the interplay between mirror and collective oscillations of the atomic density. We study the implications of this dynamics and the possibility of an indirect diagnostic. Pulsed laser light (tuned within realistic experimental conditions) is shown to induce an almost sixfold increase of the atom-mirror entanglement and to be responsible for an interesting dynamics between such mesoscopic systems. In order to assess the advantages offered by the proposed control technique, we compare the time-dependent dynamics of the system under constant pumping with the evolution due to the modulated laser light. Our predictions can be observed in a realistic setup that is central to the current quest for mesoscopic quantumness.

Unusual discrete soliton and breather modes collective excitations in Bose-Einstein condensates with tunable three-body interaction

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The dynamical evolution of collective excitations of Bose-Einstein condensates with tunable tree-body interaction is studied and it shows very unusual behavior. The dynamics is governed by discrete nonlinear Schrodinger equation.The dynamical phase diagram of the system is obtained using variational method and direct numerical solutions. The discrete breather phase totally disappears in the regime where the three-body interaction completely dominate over the two-body interaction. The soliton phase in this particular regime exist only when the soliton line approaches the critical line in the phase diagram. When weak two-body interactions are added to this regime, the discrete breather solutions reappear, but occupies a very small domain in the phase space. Likewise, in this regime, the soliton as well as the discrete breather phases completely disappear if the signs of the two-body and three-body interactions are opposite. We analyze the origin of these unusual collective nonlinear self localized excitations and conjecture that it may have some possible relation with the intriguing properties of the Efimov state.

Study of time-dynamics in a one-dimensional optical superlattice

Arya Dhar

As shown in previous works, a system of bosons loaded in optical superlattice at a filling factor of one, exhibits three phases, viz. Mott insulator (MI), superfluid (SF) and the superlattice induced Mott insulator (SLMI) depending on the value of superlattice potential, with the hopping amplitude and the on-site two-body interaction values fixed. In this work, we vary the superlattice potential linearly with time starting from the MI phase, passing through the SF phase, and ultimately stopping in the SLMI phase. We look for the residual energy as a function of the different ramp rates. Such an investigation will denote the excitations produced during such a quench.

Bond Ordering Wave in Dipolar Fermionic Mixtures

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In this study[1] we investigate the effect of dipolar interactions in commensurate one-dimensional systems in connection with the possibility of observing exotic many-body effects with trapped atomic and molecular dipolar fermi gases. Using both analytical and numerical techniques, in particular the Density Matrix Renormalization Group (DMRG) algorithm, we show how the competition between short- and long-range interactions, together with the anisotropic nature of the dipolar interaction, gives rise to frustrating effects which lead to the stabilization of spontaneously dimerized phases charachterized by bond ordering[2].

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Finite-momentum Bose-Einstein condensates in shaken two dimensional square optical lattices

Marco Di Liberto, Olivier Tieleman, Cristiane Morais Smith, and Vincenzo Branchina

We consider ultracold bosons in a two-dimensional square optical lattice described by the Bose-Hubbard model. In addition, an external time-dependent sinusoidal force is applied to the system, which shakes the lattice along one of the diagonals. The effect of the shaking is to renormalize the nearestneighbor- hopping coefficients, which can be arbitrarily reduced, can vanish, or can even change sign, depending on the shaking parameter. Therefore, it is necessary to account for higher-order-hopping terms, which are renormalized differently by the shaking, and to introduce anisotropy into the problem. We show that the competition between these different hopping terms leads to finite-momentum condensates with a momentum that may be tuned via the strength of the shaking. We calculate the boundaries between the Mott insulator and the different superfluid phases and present the time-of-flight images expected to be observed experimentally. Our results open up possibilities for the realization of bosonic analogs of the LOFF phase describing inhomogeneous superconductivity.

M. Di Liberto, O. Tieleman, V. Branchina, C. Morais Smith, Phys. Rev. A 84, 013607 (2011).

Generalized Gibbs ensemble and work statistics of a quenched Luttinger liquid

B. Dora, M. Haque, A. Bacsi, G. Zarand

We analyze the probability distribution function (PDF) of work done on a Luttinger liquid for an arbitrary finite duration interaction quench and show that it can be described in terms a generalized Gibbs ensemble. We construct the corresponding density matrix with explicit intermode correlations, and determine the duration and interaction dependence of the probability of an adiabatic transition and the PDF of non-adiabatic processes. In the thermodynamic limit, the PDF of work exhibits a non-Gaussian maximum around the excess heat, carrying almost all spectral weight. In contrast, in the small system limit most spectral weight is carried by a delta peak at the energy of the adiabatic process, and an oscillating PDF with dips at energies commensurate to the quench duration and with an exponential envelope develops. Relevance to cold atom experiments is also discussed.

Polaron dynamics and transport in the strongly interacting 2D Fermi gas

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We study the strongly interacting 2D Fermi gas at large spin imbalance and compute the full spectral functions of molecules and impurity atoms (“Fermi polarons”) [1]. Our predictions of ametastable repulsive polaron branch and its RF spectra have recently by confirmed experimentally [2]. For the transport properties of the balanced gas we find that scattering is strongly enhanced by the inclusion of medium effects [3]. This reduces the shear viscosity η and the spin diffusion coefficient Ds by a factor of three near Tc and brings the viscosity to entropy ratio close to the string theory bound $\eta/s = h/4\pi kB$. For the damping ΓQ of the quadrupole mode in the trap we obtain good agreement with recent experiments [4]. As an outlook, we argue that the thermodynamic and transport properties of the unitary Fermi gas can be understood and computed rather accurately in the framework of quantum critical points and large-N expansion [5].

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Superfluid to Mott insulator transition of bosons with local three-body interactions

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Using the density matrix renormalization group method, we determine the phase diagram of a one-dimensional system of bosons interacting via repulsive local three-body interactions. This system presents two phases: Mott-insulator and superfluid. The quantum critical point for the first lobes at constant density were determined with the block von Neumann entropy. A different reentrance phase transition for each lobe was observed.

Asymptotic limit of momentum distribution functions in the sudden expansion of a spin-imbalanced Fermi gas in one dimension

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We study the sudden expansion of a spin-imbalanced Fermi gas in an optical lattice after quenching the trapping potential to zero, described by the attractive Hubbard model. Using time-dependent density matrix renormalization group simulations we demonstrate that the momentum distribution functions (MDFs) of majority and minority fermions become stationary after surprinsingly short expansion times. We explain this via a quantum distillation mechanism that results in a spatial separation of excess fermions and pairs, causing Fulde-Ferrell-Larkin-Ovchinnikov correlations to disappear rapidly. We further argue that the asymptotic form of the MDFs is determined by the integrals of motion of this integrable quantum systems, namely the rapidities from the Bethe ansatz solution. We discuss the relevance of our results for the observation of Fulde-Ferrell-Larkin-Ovchinnikov correlations in one-dimensional systems, related to recent experiments from Rice University (Liao et al. Nature 467, 567 (2010)).

Statistical properties of ultracold bosons in bichromatic optical lattices

Krzysztof Jachymski and Zbigniew Idziaszek (University of Warsaw, Faculty of Physics)

We consider a gas of bosons in a one-dimensional optical lattice. The system is perturbed by another lattice of period incommensurate with the primary one. Such a system can be described by Aubry-Andre model [1] which predicts a transition to localized states at certain disorder strength. This system has been realized experimentally [2], confirming the localization phenomenon. We analize finite temperature properties of the system by calculating the canonical partition function using exact methods for the non-interacting and strongly interacting limit. We compute the statistical quantities of the superfluid and localized phases and of the strongly interacting gas. We show that those phases may be distinguished in experiment using off-resonant light scattering.

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G. Li

We investigate the property of a mixture of two species of pseudospin-1/2 atoms with interspecies spin-exchange, in addition to usual density-density interaction. The ground states of the system with different spin exchange interactions are obtained, as well as various low energy excitations. We find that in a certain parameter regime and in 1+1D, the effective theory describes a Sine-Gordon field coupled to a free scalar field. The renormalization group (RG) method is employed to solve the phase diagram in 1+1D.

Engineered tunable decay rate and controllable dissipative dynamics

Zhiguo Lü and Hang Zheng

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We investigate the steering dissipative dynamics of a two-level system (qubit) by means of the modulation of an assisted tunneling degree of freedom which is described by a quantum-oscillator spin-boson model. Our results reveal that the decoherence rate of the qubit can be significantly suppressed and simultaneously its quality factor is enhanced. Moreover, the modulated dynamical susceptibility exhibits a multi-peak feature which is indicative of the underlying structure and measurable in experiment. Our findings demonstrate that the interplay between the combined degrees of freedom and the qubit is crucial for reducing the dissipation of qubit and expanding the coherent regime of quantum operation much large. The strategy might be used to fight against deterioration of quantum coherence in quantum information processing.

Finite temperature effects in two-mode bosonic Josephson junctions

Giovanni Mazzarella

We analyze the effects of the temperature on a bosonic Josephson junction realized with ultracold and dilute atoms in a double-well potential. Starting from the eigenstates of the two-site Bose-Hubbard Hamiltonian, we calculate the coherence visibility and the fluctuation of the on-site occupation number and study them as functions of the temperature. We show that, contrary to naive expectations, when the boson-boson interaction is suitably chosen thermal effects can increase the coherence visibility and reduce the on-site number fluctuation.

Quantum Phases of Bosons in a Bose Ladder with Magnetic Flux

Tapan Mishra

Motivated by experiments on Josephson junction arrays, and cold atoms in an optical lattice in a synthetic magnetic field, we study the "fully frustrated" Bose-Hubbard model(FFBH) with half a magnetic flux quantum per plaquette. We obtain the phase diagram of this model on a two-leg ladder at integer filling via the density matrix renormalization group approach, complemented by Monte Carlo simulations on an effective classical XY model. The ground state at intermediate interaction is consistently shown to be a chiral Mott insulator (CMI) with a gap to all excitations and staggered loop currents which spontaneously break time-reversal symmetry. Along with this we obtain the chiral superfluid (CSF) phase with loop current order and the a regular Mott insulator phase for small and large interactions respectively.

High correlation between flux of particles and entanglement for quantum gases in a ring lattice

Luis Morales Molina

We study the generation of entanglement for two distinct atomic species in a ring shaped optical lattice. By turning on the interaction between the species entanglement is generated, thus leading to the modification of the atomic currents. It is found that the current of one of the species can be used as a good indicator of entanglement generation. A proposal for an experimental setup is discussed.

Hirota Method for Multi-soliton solutions of the Non-linear Schrodinger Equation with an arbitrary Quadratic time-dependent Potential

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Within the past few decades soliton theory has attracted considerable attention in diverse physical applications and the various mathematical methods of solving the resulting evolution equations. The mathematical methods of solving such equations are usually direct as well as indirect. Here we intend to construct multi-soliton solutions of a physically significant evolution equation (the Non-linear Schrodinger Equation with an arbitrary quadratic time-dependent potential) using the Hirota method. Unlike many other methods (notably the inverse scattering techniques,) the Hirota method is algebraic, rather than being analytic. Thus if one is only interested in finding multi-soliton solutions, the Hirota method is the fastest in producing results.

Anderson localization of pairs in bichromatic optical lattices

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We investigate the formation of bound states made of two interacting atoms moving in a one dimensional (1D) quasi-periodic optical lattice. We derive the quantum phase diagram for Anderson localization of both attractively and repulsively bound pairs. We calculate the pair binding energy and show analytically that its behavior as a function of the interaction strength depends crucially on the nature -extended, multi-fractal, localized- of the single-particle atomic states. Experimental implications of our results are discussed.

A new experimental setup for quantum simulation with atomic Ytterbium

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Ytterbium is a two-electron atom which has many stable isotopes (both fermionic and bosonic) and good collisional properties. Having a highly metastable state and lack of electron spin, it offers unique opportunities to investigate many different types of physics like the simulation of artificial gauge fields [1-2] and SU(N) physics [3]. Moreover Ytterbium inspired intriguing theoretical proposals to perform quantum information processing [4-5].

We report on the recent achievement of Bose-Einstein condensation of the ^{174}Yb isotope. In the next stage of the experiment we will trap Yb BEC and Fermi gases in optical lattices in order to explore the most interesting possibilities offered by this atom for quantum simulation, in combination with internal state manipulation and single-site imaging through a high-NA objective.

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Wave packets in an ultracold lattice gas

Poul Lindholm Pedersen

Wave packets are important in physics, dating back to the formulation of quantum mechanics. We show that it is possible to produce wave packets from a BEC in a combined 1D optical lattice and magnetic trap by amplitude modulating the lattice. These wave packets can be deexcited into localised states that arise from the magnetic potential shift between lattice sites.
This mechanism allows for investigations of the coherent dynamics of the excited state in direct analogy with pump-probe spectroscopy. In-situ measurements of the process allows us to monitor the movement of wave packets on the relevant time scale. Tuning the parameters of the modulation pulses also allows gains access to different bands in the lattice, both the strongly confined states and high-momentum freely propagating states.
The process is also capable of realising a matter-wave splitter where an abitrary fraction of the wave packet may be deexcited into a localised states.

Quantum Breathing of an Impurity in a One-dimensional Bath of Interacting Bosons

Sebastiano Peotta

By means of time-dependent density-matrix renormalization-group (TDMRG) we are able to follow the real-time dynamics of a single impurity embedded in a one-dimensional bath of interacting bosons. We focus on the impurity breathing mode, which is found to be well-described by a single oscillation frequency and a damping rate. If the impurity is very weakly coupled to the bath, a Luttinger-liquid description is valid and the impurity suers an Abraham-Lorentz radiation-reaction friction. For a large portion of the explored parameter space, the TDMRG results fall well beyond the Luttinger-liquid paradigm.

References:
arXiv:1206.3984

Ultracold atoms in optical lattices: beyond the Hubbard model

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We investigate the properties of strongly interacting atomic gases in optical lattices, addressing the regime of weak and intermediate optical potentials where the conventional description in terms of the single band Hubbard model is not reliable. In the case of bosonic atoms, we introduce a novel hybrid Monte Carlo technique which allows to simulate the superfluid to insulator transition in continuous space, thus going beyond the single-band approximation [1]. We compare the Monte Carlo results with experimental data [2], finding excellent agreement.
For fermions, we apply Kohn-Sham Density Functional Theory (DFT), which is the most powerful computational tool routinely used in material science to simulate the electronic structure of solids. In this work, we use a new energy-density functional for repulsive Fermi gases with short-range interactions, as opposed to the Coulomb interaction in electronic systems. The first results based on a local spin-density approximation [3] show evidence of a ferromagnetic phase due to repulsive interactions, and of anti-ferromagnetic order at half filling. As an outlook, we will discuss how the development of DFT for ultracold atomic gases can form abstrong link between materials science and atomic physics.

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High-sensitive magnetometry using coherent laser atom interaction

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High sensitive magnetic field measurement is not only fundamental requirement of all electromagnetic phenomena, but also has technological application in geophysical mapping, underground detection, and most importantly in biomagnetism. The indispensible role of superconducting quantum interference devices (SQUID) as high-sensitive magnetic field sensor has been challenged by the rapid growth in research involving atomic sensor. These atomic magnetometers have reached short term sensitivity in the sub-femto tesla regime, which is better than the sensitivity of the SQUID based magnetometer. Further, the atomic magnetometers are advantageous as they operates at room temperature and don't require any cryogenic cooling. In view of these advantages, they are expected to dominate ultra-high sensitive magnetic field measurements in near future.

In our laboratory, we have developed a new kind of atomic vector magnetometer based on a hybrid technique comprising of coherent population trapping (CPT) and polarization rotation in atomic ensemble [1,2]. Our device does not require a bias magnetic field and continuous calibration of the field insensitive transition is irrelevant as required by the conventional CPT based magnetometer. We have demonstrated the operation of this device in a bench-top model. This device can be miniaturized to chip-scale as has been demonstrated for the CPT based magnetometer.

In this presentation, the methods of operation of this new kind of magnetometer will be discussed. Our ongoing research for improving the sensitivity of the magnetometer, miniaturization of the device and coherent population trapping with ultra-cold atoms will be summarized.

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Ultracold atomic gases at negative absolute temperatures

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Ultracold atomic clouds are used to simulate a broad range of complex quantum systems with a high degree of experimental control. Current techniques also allow for a realization of an out-of-equilibrium situation where the system relaxes to a state with negative absolute temperature, $T<0$. Under these conditions, higher energy levels are more likely occupied than lower energy levels. As a consequence, bosonic atoms in an optical lattice condense at finite momenta, at the maxima instead of the minimum of the kinetic energy. A further interesting possibility of using $T<0$ is that one can experimentally reach new parameter regimes. This idea could be applied to simulate the SU(3) attractive Hubbard model with repulsively interacting atoms, which can prove useful to understand some puzzles of quantum chromodynamics.

Density wave super solid and Mott insulator-superfluid transition in presence of an ‘artificial’ gauge field: Mean field and Strong Coupling results

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We study the effect of an artificial gauge field on the zero temperature phase diagram of extended Bose Hubbard model, that describes ultra cold atoms in optical lattices with long range interaction. Using Mean field approach, we demonstrate the structural differences between vortex in a supersolid and superfluid. We determine analytically the effect of the artificial gauge field on the density wave - supersolid (DW-SS) and the the Mott insulator-superfluid (MI -SF) transition boundary. Using Strong Coupling perturbative calculations, the momentum distribution at these two transition boundaries is also calculated. It is shown that such momentum distribution which can be observed in time of flight measurement, reveals the symmetry of the gauge potential through the formation of magnetic Brillouin zone and clearly distinguishes between the DW-SS and MI-SF boundary. We also point out that in symmetric gauge the momentum distribution structure at these transition boundaries bears distinctive signatures of vortices in supersolid and superfluid phases.

Global and local condensate and superfluid fraction of a few hard core bosons in a combined harmonic optical cubic lattice in continuous space

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The Bose-Einstein condensate (BEC) in separate wells is a relatively old idea [1]. For example, a double well with two condensates tunneling between the wells [2] with some Josephson-Junction effect [3] is indeed just that. Earlier, spatially separated BECs were realized in the experiment of Andrews et al. [4], where a condensate was split into two parts and then allowed to rejoin. The natural extention of the double well is then a multiwell trap, such as in an optical lattice (OL). Here, we particularly aim at treating BECs in multiwell traps as being totally independent from each other. We consider a multiwell system embedded inside a harmonic oscillator (HO) trap with the wells being arranged in a cubic lattice. This constitutes a combined harmonic optical cubic lattice (CHOCL).

The chief goal of our work is to emphasize the rather exotic concepts of localized superfluidity and BEC. We clearly distinguish between their global and local quantities. The local quantity is the one measured in each CHOCL well, whereas the global one in all wells. We focus on the role of the overlap between the localized BEC in one well and the BECs in all-neighbor wells, being motivated by the work of Baillie and Blackie [5].

The gobal and local condensate fraction (CF) and superfluid fraction (CF) is computed as a function of the hard core diameter of the bosons. Our chief result is an opposing behavior of the global and local CF and SFF with increasing OL wave vector. In addition, the CF in a lattice well is enhanced by the overlap with the local BECs in all neighbor wells. The global SF is depleted, whereas the global CF remains almost constant with increasing HC repulsion.

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Energy and condensate dynamics of a two-dimensional trapped Bose gas excited by a red-detuned laser potential

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The investigation of a Bose-Einstein condensate (BEC) excited by a moving obstacle, produced by a blue-detuned Gaussian laser potential, has received considerable theoretical and experimental interest [1,2]. The motion of this obstacle, whether linear or rotational, causes excitations leading to strikingly interesting phenomena such as vortices [3-6], solitons [7], crescent vortex solitons [8], and dispersive waves accompanying the solitons [9]. Moreover, it has been demonstrated that an obstacle moving inside a two-dimensional (2D) power-law trap plus hard-wall box-potential (HWBP) boundaries can lead to fascinating self-interfering matter
wave patterns [10].
In this work, we study the dynamics of a BEC by numerically solving the time-dependent Gross-Pitaevskii equation applying a Crank-Nicolson code developed earlier [11]. We use a moving attractive obstacle generated by a red-detuned laser potential (RDLP) to explore the energy and condensate dynamics of a 2D trapped (BEC) inside HWBP boundaries. Starting from the center of the external trap, the attractive obstacle is a “dimple” trap which transports solitons to the HWBP. When the dimple reaches the HWBP, the soliton collides with the hard wall and is reflected towards the center of the trap. After reflection, it begins to decay as can be observed from a decaying oscillatory pattern of the energy dynamics. We find that the lifetime of the solitons after reflection is governed by the shape of the trapping potential. Further, we demonstrate that the condensate dynamics depends on the velocity of the RDLP.

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An ultracold ytterbium quantum gas for many-body physics

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Ultracold atoms in optical lattices have already proven to be excellent prototype systems for condensed matter physics simulation and quantum information processing. Well-known Hamiltonians that play an important role in condensed matter systems like the Bose-Hubbard or Fermi-Hubbard Hamiltonian can be studied on the microscopic level.

Alkaline-earth-type atoms with their bosonic and fermionic isotopes have some attractive properties that make them suitable for accessing
new regimes of many-body physics. They possess a long-lived excited state which can be used to implement state-dependent optical lattices, enabling the realization of more complex classes of Hamiltonians. In addition the high nuclear spin of one of the fermionic isotopes, which at the same time is highly decoupled from the electronic state, gives rise to an enlarged SU(N) symmetry of the Hamiltonian. Theory predicts new ground state phases with magnetic ordering at sufficiently low temperatures for such systems with high SU(N) symmetry.

We will present our new setup designed for cooling ytterbium to degenerate regime and outline plans for quantum simulation experiments in state-dependent optical potentials.

Entanglement of alkaline-earth-metal fermionic atoms confined in optical lattices

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We calculate the entanglement of the ground state of alkaline-earth-metal fermionic atoms confined in one-dimensional optical lattices. This system can be described using the Kondo lattice model plus a harmonic confining potential, and we adopt the density-matrix renormalization group to study its ground state.We find that the local von Neumann entropy is constant in the insulating domains, and a one-to-one correspondence with the variance of the local density is observed. We show that the average entropy and its derivative are useful tools for identifying quantum transitions in impurity systems.

Metamaterial analogy of electromagnetically induced transparency in waveguide configuration

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Electromagnetically induced transparency (EIT) is a typical quantum phenomenon where destructive quantum interference modifies the optical response of an atomic medium resulting in a narrow transparent spectrum window within the original absorption line with extremely steep dispersion [1]. However, in an atomic EIT system, some parameters, for example the decay rate, are very difficult to be adjusted, and the time evolution is at the order of 10-10 s that is difficult to be detected.

Metamaterials (MMs, metallic subwavelength structures) with geometry-dependent localized plasmon modes are excellent candidates for realizing the classical analog of quantum ones. Recently, metamaterial analog of electromagnetically induced transparency (EIT) phenomenon has been proposed and then experimentally demonstrated [1-5]. This analogy between classical and quantum systems not only presents a physical intuition for the coherent phenomena occurring in atomic systems [6], but also aims to the potential applications, such as sensing and “slowing light” at room temperature, etc.

In this poster, the metamaterial EIT with tunable loss rate, which is the analog of decay rate in atomic counterpart, is studied based on waveguide configuration. Each EIT element consists of a comb line and split-ring resonators (SRRs), which serve as the “bright” and the “dark” resonator, respectively. A transmission window with nearly unchanged maximum transmittance is observed as the result of simultaneous suppression of reflection and absorption. Two important parameters for slow-light applications are studied. It is shown that the transmission-delay product (TDP) is almost independent of the intrinsic loss while the bandwidth-delay product (BDP) is affected.

Our wave guided EIT structure may be extended to the design of low-loss device in nanoplasmonic circuits where the intrinsic loss plays an important role [7]. Moreover, the dynamic evolution of EIT in metamaterials, which is still not very clear due to its difficulty to be detected in atomic EIT systems, is investigated for the first time by visualizing the evolution of current magnitude in the bright resonator. This kind of dynamic study mimics the population transfer between energy levels in the atomic EIT system in one hand. On the other hand, it gives parameters determining the EIT building process in metamaterials that is important for applications involving rapid optical response. Finally, we numerically studied metamaterial analogy of a four-level tripod system, where double dark resonances are applied. The interference results in strong absorption (and reflection) at the line center of EIT.

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Emergence of Quintet Superfluidity in the Chain of Partially Polarized Spin-3/2 Ultracold Atoms

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The system of ultracold atoms with hyperfine spin $F=3/2$ might be unstable against the formationof quintet pairs if the interaction is attractive in the quintet channel. It was shown earlier that in unpolarized system different quartetting phases are energetically more favorable than quintet pairs [1]. Nevertheless, it is expected that finite population imbalance of the different spin components can destroy the phase of singlet quartets permitting of other superfluid like instability with additional magnetic order. Thus motivated we studied the possible formation of local quintet pairs and their stability in a one-dimensional chain of fermionic atoms with hyperfine spin $F=3/2$ [2]. We have found that in fact spin-population imbalance induced for instance by external magnetic field can stabilize different quintet pair states. For sufficiently large population imbalance ---when two spin components are frozen out and the remaining two components with $F_z=3/2$ and $F_z=1/2$ form an effective spin-1/2 system--- we have found an FFLO-like state of $m=2$ quintet pairs. Similar FFLO phase recently has been realized experimentally and studied by the group of Hulet and Mueller [3]. Contrary, for intermediate values of the magnetization even more exotic superfluidity of coexisting quintet pairs with different magnetic moments becomes dominant. The inner structure of these quintet superfluid phases depends on the scattering length in the singlet and quintet channels. This type of behavior characterizes the system for moderated population imbalance in a broad range of the parameter space including also the high SU(4) symmetric case that is the most relevant situation with respect to alkaline earth atom experiments. Since our model contains only s-wave interaction, this result might also open new direction for experimental realization and studies of nonsinglet pairing with ultracold atomic systems.

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Spin squeezing for a system of N atomic two-level systems in a resonant cavity

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The orientation and fluctuations of the total spin, in a system of N two-level atoms placed in a resonant cavity, and interacting with a single cavity mode and among themselves, are studied. The squeezing parameter of the system is calculated by using exact solutions. We calculated the time evolution of the populations of the atomic states and relate it with the spin-squeezing parameter. We studied the dependence of the squeezing factor with the number of atoms N and the initial conditions.

NS junction based on a 3D topological insulator in a perpendicular magnetic field

Rakesh P Tiwari

A normal-superconducting (NS) junction based on the surface states of a strong 3Dtopological insulator, with a finite chemical potential is shown to support a zero energy chiral Majorana mode in the zeroth Landau level in the presence of a perpendicular magnetic field. The velocity of this Majorana mode can be tuned by changing the chemical potential or the external magnetic field allowing for efficient control over the Majorana mode. As the chemical potential increases there comes a point in the parameter space when higher Landau levels (electron like or hole like) start contributing to the low energy properties of this junction enabling the Majorana mode to influence the edge magnetoplasmons along the junction.

The Higgs mode in a superfluid of Dirac fermions

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Motivated by the recent experimental developments on ultracold Fermi gases in a honeycomb optical lattice [1], we study collective modes of atomic Dirac fermions in the honeycomb lattice. The attractive fermion Hubbard model on the two-dimensional honeycomb lattice was found to exhibit a quantum phase transition at half-filling between a semimetal with massless Dirac fermion excitations and a simple s-wave superfluid phase [2]. We calculate collective modes in superfluid phase as well as in normal phase at half-filling in the vicinity of the quantum critical point.
We find evidence for a well-defined gapful amplitude mode called Higgs mode below the two-particle continuum, together with a gapless Anderson-Bogoliubov (AB) mode in superfluid phase. As approaching the quantum critical point from the superfluid side, the energy gap of the Higgs mode decreases and eventually the Higgs mode and AB mode become degenerate at the quantum critical point. In the normal phase, we find that these collective modes become particle-particle and particle-hole bound states called Cooperon and exciton. We discuss possibilities for observing these collective modes in optical lattice experiments.

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Quantum simulation of 2D strongly-correlated fermions

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Ultracold atoms are ideal quantum simulators due to the unprecedented possibility of controlling the relevant physical parameters. Infact they are perfect environments where to implement quantum models and where to study condensed matter problems.
We present our project on simulating strongly-correlated bidimensional fermionic systems by using ultracold gases of 6 Li atoms. We aim at investigating the effects of reduced dimensionality on the BEC-BCS crossover also in the presence of a controllable disorder. We want also to study Josephson-like tunneling between layers, measuring the superfluid gap. The final goal will be to implement Fermi-Hubbard Hamiltonians that are expected to unveil the fascinating but still debated physics of high-Tc superconductors.

Stable spatial solitons in binary mixtures of Bose-condensates

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Mixtures of Bose-Einstein condensates are interacting quantum systems of macroscopic scale which exhibit rich physics not accessible in a single-component degenerate quantum gas. They open up intriguing possibilities for a number of important physical applications, including quantum simulation, quantum interferometry, and precision measurements. Experimentally, multi-component BECs are generated as mixtures of atoms in different hyperfine states or by simultaneously trapping different atomic species.

One of most prominent nonlinear objects that can emerge in attractive Bose-Einstein condensate (BEC) is a bright soliton, which is a spatially localized nonlinear matter-wave structure. It is well known, that two- and three-dimensional bright solitons are unstable with respect to collapse if their number of particles is overcritical. The simple idea to arrest the collapse is to use a mixture of atoms with repulsive inter-component interaction. It turns out, that soliton-soliton pairs in trapless two-component BEC are unstable – the more powerful component collapses [1]. In present work we study solitonic structure in two-component mixtures of trapped BECs. We consider different geometries of “disk-shaped” trapping potential including parabolic trap and toroidal trap. We perform detailed theoretical analysis of solitonic steady-states and investigate their stability. Different scenarios of unstable evolution have been observed. The region of the stability of soliton-soliton pairs is found [3].

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Anomalous hysteresis of Bose gases in an optical lattice

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We study metastability and hysteresis of Bose gases loaded into optical lattices. Some systems, such as dipolar bosons in a triangular lattice [1] and spin-1 bosons in a cubic lattice [2], are expected to exhibit a first-order transition with phase reentrance. For example, in the former case, solid and supersolid phases are sandwiched in between superfluid regions, and the system shows a reentrant behavior from superfluid to solid (to supersolid), and back to superfluid with varying the chemical potential. We find that such a reentrant first-order transition can generally show a particular hysteresis behavior; the phase transition can occur only unidirectionally from one phase to another, and the hysteresis curve does not form a conventional hysteresis-loop structure. The origin of this anomalous hysteresis is explained by the Ginzburg-Landau theory for reentrant first-order phase transitions.

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Opposite effect of spin-orbit coupling on condensation and superfluidity

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Realization of spin-orbit coupling (SOC) in cold atomic systems (1) makes it possible to study novel phenomena in this highly controllable system. One interesting problem is the effect of SOC on the so-called BCS-BEC crossover problem (2,3). For a Rashba type SOC(x-y direction), we found that SOC enhances the condensed density while suppresses the superfluid motion in the x-y direction. We point out that the Landau formula of the superfluid density based on the Galilean invariance is invalid in the SOC Fermi system (4).

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