Strongly correlated phases of matter realized with ultracold atoms

Final report for project 104652

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Introduction

Experimental realization of Bose-Einstein condensation in dilute vapors of alkali atoms in 1995 (see for a review [1]) turned experiments with ultracold atoms into a flexible tool for discovering new phenomena and reproducing old ones encountered in different areas of physics. Later, in 2001, as a token of recognition a Nobel price has been awarded to the leaders of the two pioneering research groups. The interest toward this field is mainly motivated by the very good amount of control on atomic systems rendering the experimental observation of complicated phases of matter well tractable. With the help of scattering resonances it is even possible to control the atom-atom interaction essentially arbitrarily in experiments by tuning an external magnetic field. Moreover, the sophisticated experimental techniques made it possible to choose the system parameters in such a way to synthesize or ”simulate” important properties of the effects found in their original appearance, which are often dirtier or simply harder to investigate. Sometimes cosmological phenomena have been demonstrated in superfluid many-body systems.

One of the most intense area of investigation now in this field is related to condensed matter physics. The motion of trapped atoms inside the periodic potential formed by counterpropagating laser beams, the so-called optical-lattice, realizes naturally solid state physics phenomena in well controlled, ideal, or even in modified circumstances (see for instance Ref. [2]). The variety of atomic/molecular species (both bosons and fermions) and that of the experimental techniques opened up an avalanche of possible investigations. The major experimental tools are electromagnetic fields, and laser beams, which help to maintain the atoms/molecules in the appropriate states, transport or even cool them. One of the main tasks for theoreticians is to propose experimental schemes that realize important phenomena, and to chart the parameter region where the desired effect takes place. The other task is to go beyond the possibilities of the old models and forecast new effects arising in the versatile ultracold atom context.

Summary of the results

The research was focused on models which a) are realistic with today’s experimental technology, b) realize important models of condensed matter and/or of high energy physics. The investigations are divided into two work packages (WP1 and WP2) which supplement each other but form separate logical blocks.

WP1 – Emulators of quantum magnetism

In this work package we addressed the possibilities of realizing Mott insulators with nontrivial magnetic correlations. The main motivation was to understand better the antiferromagnetic correlations, which play an important role in the explanation of the phase diagram of high-temperature superconductors. However, in our case the systems under consideration were not the traditional condensed matter samples, but rather dilute vapors of ultracold atoms loaded to an optical lattice. The Mott insulator state of these vapors emerges at low temperatures and for sufficiently strong interactions, when there is an equal number of atoms as the number of lattice sites. In this limit, the multiple occupancy of a site becomes energetically forbidden, and the atomic motion freezes. However, the spins carried by the atoms can exchange by two successive virtual hoppings.

We studied spin-liquid phases of spin-5/2 alkaline-earth-metal atoms on a honeycomb lattice at finite temperatures. An interesting property of alkaline-earth-metal atoms, is that both the net orbital angular momentum and net spin of the electrons are zero. Therefore, the hyperfine spin of the atom is purely its nuclear spin. As the nuclear spins of the atoms do not interact with each other, the atomic scattering is independent of the spin of the atoms. Therefore, atomic scattering becomes SU(6) symmetric, instead of being symmetric with respect to the 6 dimensional representation of SU(2). In the framework of a path-integral formulation, which is a reformulation of the Gutzwiller projection variational approach, we performed a saddle-point approximation and determined spin liquid-phases with the lowest free energy and studied their temperature dependence. We identified a critical temperature, where all the spin liquid phases melt and the system goes to the paramagnetic phase. We also studied the stability of the saddle-point solutions and showed that a time-reversal symmetry-breaking state, a so called chiral spin-liquid phase is realized even at finite temperatures. We determined the spin structure factor, which, in principle, is an experimentally measurable quantity and is the basic tool to map the spectrum of elementary excitations of the system [3].

We also studied the phase diagram of spin-3/2 alkaline atoms also on a honeycomb structure. The main motivation was to find a way to realize the AKLT (Affleck, Kennedy, Lieb, Tasaki) state, which is important both in condensed matter and in quantum information. To this end we generalized the mean-field theory we have been using for the SU(N) symmetric Hubbard models now to higher dimensional SU(2) representations. The presence of multiple coupling constants and the ambiguity in choosing the unit cell made the mean-field calculations more cumbersome than what have been anticipating. We have solved the mean-field equations for various parameter values and obtained the phase diagram of the system at zero temperature. We found that in a large part of the parameter space the system realizes classical ferromagnetic or Néel order, but in an experimentally relevant, extended region an AKLT like entangled pair state has the lowest energy. It is remarkable that when the magnitude of the spin dependent coupling constant is increased in the ferromagnetic side, this state goes to the ferromagnetic state through and intermediate phase, where both site centered ferromagnetic and bond centered orders are present simultaneously. Similar intermediate state was not found in the antiferromagnetic side of the coupling [4].

We also studied the magnetic properties of spin-3/2 alkaline-earth-metal atoms on a face-centered-cubic lattice. Due to the higher symmetry of alkaline-earth-metal atoms, the low energy physics is described by an SU(4) symmetric exchange model. As the lattice is three dimensional, we expect symmetry breaking at low temperatures. We found, that classical ordering leads to a macroscopically degenerate ground state. However, the inclusion of fluctuations above the classically ordered state removes the degeneracy and selects a four-sublattice symmetry-breaking ground state. This is a nice example of the order-by-disorder mechanism [5].

WP2 – Superfluids inside optical resonators

In this work package we studied the interaction between a Bose-Einstein condensate and the electromagnetic field of a single-mode optical resonator. Here, the main motivation is to study strongly interacting systems with an infinite range interaction.

We showed that a laser-driven Bose-Einstein condensate of ultracold atoms loaded into a lossy high-finesse optical resonator exhibits critical behavior and, in the thermodynamic limit, a phase transition between stationary states of different symmetries. The system realizes an open-system variant of the celebrated Dicke model. We studied the transition for a finite number of atoms by means of a Hartree-Fock-Bogoliubov method adapted to a damped-driven open system. The finite-size scaling exponents are determined and a clear distinction between the nonequilibrium and equilibrium quantum criticality is found [6].

We studied the effect of atomic s-wave collisions on a Bose-Einstein condensate also strongly interacting with a single mode of a high-finesse optical cavity. We showed that atom-atom collisions merely renormalize parameters of the usual optomechanical interaction. Moreover, we showed that even in the case of strong harmonic confinement – which invalidates the use of Bloch states – a single excitation mode of the Bose-Einstein condensate couples significantly to the light field, that is the simplified picture of a single "mechanical" oscillator mode remains valid [7].

Continuing the investigation of effects caused by the interatomic s-wave scattering, we studied the properties of the elementary excitations of a bosonic superfluid inside a single mode optical resonator. As a result of the nonlinearities produced by the interaction the quasiparicles acquire a finite lifetime. We showed that the Beliaev damping of elementary excitations in a homogeneous Bose-Einstein condensate can undergo resonant enhancement by several orders of magnitude when the superfluid is interacting with a far-detuned radiation field of an optical resonator. The photonic tuning of the quasiparticle damping can be controlled by an external laser drive. An interesting mathematical aspect of the problem is that the Born-Markov approximation fails to predict the location of the quasiparticle pole correctly due to the huge shift of the location of the exact pole from that of the the non-interacting one. Accordingly the self-energy had to be treated with care and continued analytically numerically [8, 9].

We studied the behavior of bosonic Josephson junctions in the presence of an additional, adjustable depth potential well in the center of the double-well barrier. This "third well" is created with a tightly focused laser beam. In our proposal the beam in the center is much narrower than the barrier, and it creates a tunable depth well which can support a localized state in the middle. We showed that the presence of the localized state in the central well changes the sign of the tunneling constant between the left and the right wells and therefore controls the fixed-point dynamics of the bosonic Josephson junction. This proposal has practical value in applications in atom-interferometry where abrupt changes in the system parameters can be very useful [10].

As a next step, the central laser was replaced by the radiation field of a single mode cavity. The cavity field is driven by a laser red detuned from the bare cavity resonance. The atomic tunneling process is strongly affected by the cavity field. On the other hand, the dynamically changing spatial distribution of the atoms can shift the cavity in and out of resonance. At resonance the photon number is hugely enhanced and the atomic tunneling becomes amplified. We revisited the Josephson-junction equations and calculated the phase diagram. We found solutions with finite imbalance and at the same time found a lack of self-trapping solutions due to the emergence of a new separatrix resulting from enhanced tunneling [11]. By exactly treating the atomic dynamics, we showed that both the self-trapping solutions and the formation of Schrödinger's cat states can be achieved with interatomic interactions weaker than those required in the absence of cavity [12].

Closing remarks

During the course of the project 7 journal articles appeared in peer-reviewed journals, 2 manuscripts are prepared and submitted for evaluation, and 1 manuscript is still under preparation for submission. Also thanks to the OTKA funding, previous collaborations could have been maintained and a new collaboration with the University of Padova was formed. A PhD student, under to co-supervison of the project PI, successfully written and defended his thesis.

The first paper [6], whose topic was part of the project's proposal, originally planned for the second year, was published before the starting date of the project. This happened because experimental applications motivated us to carry out the calculations as fast as possible, in order to give prediction of the critical exponents. The paper is appreciated in the community.

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