On the Dirty Boson Problem

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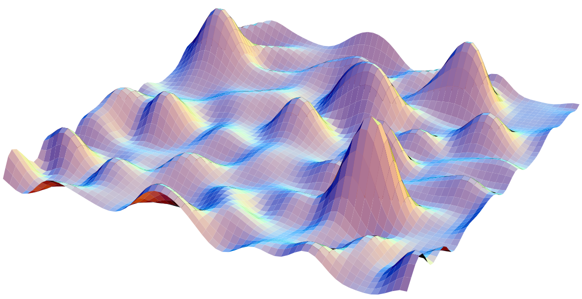
Since 1995, when Bose-Einstein condensation in ultracold atomic gases has been realized experimentally, there has been a number of further substantial breakthroughs. Today, systems of ultracold bosonic and/or fermionic quantum gases allow for an experimental control on a very high level concerning, e.g., the underlying trap geometry and the interaction strength. Moreover, they lend themselves to precise theoretical calculations of their static and dynamic properties, thus leading to highly accurate comparisons of experiment and theory. Ultracold atomic and molecular matter can be employed to provide practically ideal realizations of paradigmatically important many-body models considered in various fields, such as atomic and molecular physics, solid-state physics, and even nuclear physics. The talk discusses one illustrative example where a detailed study of ultracold atomic matter provides important insights into condensed matter physics.

To this end we review recent progress on understanding the properties of ultracold bosonic atoms in potentials with quenched disorder. This notoriously difficult *dirty boson problem* is experimentally relevant for the miniaturization of Bose-Einstein condensates on chips and can also be studied by tailoring disorder potentials via laser speckle fields. Theoretically it is intriguing because of the competition of localization and interaction as well as of disorder and superfluidity. We start with determining within a Bogoliubov theory how the collective mode frequencies of a condensate in a harmonic trap are shifted by the presence of additional weak quenched disorder. Then we calculate the perturbative shift of the critical temperature T_c which characterizes the onset of Bose-Einstein condensation for an ultracold dilute atomic gas in a harmonic trap due to weak disorder. Finally, we develop a Hartree-Fock mean-field theory for a homogeneous disordered Bose gas and study the resulting phase boundaries for the gas, the superfluid phase as well as the Bose-glass phase.



Pair–distribution function of ideal quantum gases

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Abstract:

The pair–distribution function (PDF) of ideal quantum gases, obtained by evaluating the static structure factor for a grand–canonical ensemble ("static route"), is shown to agree with the dynamic–route results derived in [1]. The PDF temperature dependence is discussed and confronted with experimental results [2]. Finally, it will be demonstrated that the PDF of condensed bosons will *not* be marred by the "pathology of the grand–canonical ensemble" [3].

References

[1] J. Bosse, K. N. Pathak, and G. S. Singh. Analytical pair correlations in ideal quantum gases: Temperature–dependent bunching and antibunching. *Physical Review E*, 84:042101(4), 2011. http://arxiv.org/abs/1109.3407v1.

[2] M. Schellekens, R. Hoppeler, A. Perrin, J. Viana Gomes, D. Boiron, A. Aspect, and C. I. Westbrook. Hanbury Brown Twiss Effect for Ultracold Quantum Gases. *Science*, 310:648, 2005.

[3] Robert M. Ziff, George E. Uhlenbeck, and Mark Kac. The Ideal Bose-Einstein Gas, Revisited. *Physics Reports (Section C of Physics Letters)*, 32, No. 4:169–248, 1977.

Properties of Trapped Bose Gas in a Large Gas Parameter Regime

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Universal Dynamics of Strongly Interacting Bosons in a Tilted Optical Lattice

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Abstract

We study the non-equilibrium dynamics of one-dimensional Mott insulating bosons in the presence of a tilted optical lattice (effective electric field E). The lattice tilt takes the system across a quantum critical point (QCP) that separates a dimerized phase (at large tilt) from a translationally symmetric phase (at low tilt). We provide an exact numerical computation of the residual energy Q, the log-fidelity F , the excess defect density D, and the order parameter correlation function for a linear-in-time variation of E with a rate v. We discuss the temporal and spatial variation of these quantities for a range of v and for finite system sizes as relevant to realistic experimental setups [J. Simon et al., Nature 472, 307 (2011)]. We show that in finite-sized systems Q, F , and D obey Kibble-Zurek-like scaling, and suggest further experiments within this setup to test our theory.

Nonlinear Excitations in BEC in Presence of a Harmonic Trap and Optical Lattice

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Abstract

We analyse the nonlinear solitonic excitations in BEC using the mean field GP equation. The presence of harmonic trap is taken into account and in the process we demonstrate the coherent control of these extended objects. The procedure to compress and accelerate them is shown. We also study the excitations in the optical lattice and show the dynamical phase transition for the shallow lattice case.

Dipolar Bose-Einstein Condensates

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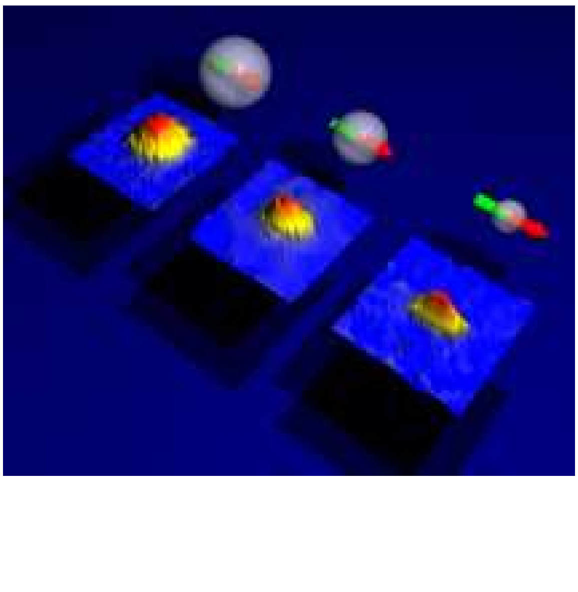
In recent years, dilute quantum degenerate gases interacting through the long-range and anisotropic dipole-dipole interaction have attracted much attention. At first, magnetic dipolar effects have been unambiguously demonstrated in atomic Bose-Einstein condensates of ^{52}Cr, ^{87}Rb, and ^{7}Li. In addition, further fascinating possibilities have been recently opened, as fermionic ^{40}K^{87}Rb molecules with an electric dipole moment of about 0.5 Debye were brought close to quantum degeneracy by using stimulated Raman adiabatic passage to efficiently convert these heteronuclear molecules into their rovibrational ground state. Due to a large electric dipole moment, the dipole-dipole interaction between such molecules might be up to 10, 000 times larger than in magnetic atomic systems. In this talk we restrict ourselves to theoretically investigate the static and the dynamic properties of polarized dipolar Bose-Einstein condensates at zero temperature.

To this end we calculate beyond-mean-field corrections to the physical quantities of interest for both homogeneous and harmonically trapped systems by working out the Bogoliubov-de Gennes theory. In the homogeneous case, we determine the Bogoliubov amplitudes and use them to evaluate the condensate ground-state energy beyond the mean-field approximation, the condensate depletion due to interactions, and the corresponding Lee-Huang-Yang correction to the equation of state. The corrected chemical potential is, then, used to obtain the Beliaev term for the sound velocity. In the trapped condensate, we derive the Bogoliubov excitation spectrum analytically within the local density approximation. By calculating the beyond-mean-field correction to the ground-state energy, we determine the corresponding equations of motion for the Thomas-Fermi radii of the condensate. In equilibrium, we obtain from these equations the quantum correction to the mean-field Thomas-Fermi radii. In addition, we also discuss the influence of quantum fluctuations on the mean-field stability diagram. Since dynamic properties constitute a key diagnostic tool for ultracold gases, we also consider the quantum corrections to the low-lying oscillation frequencies as well as to the time-of-flight expansion of the condensate. Due to the interplay between the dipolar interaction and the condensate geometry, we find that the influence of quantum fluctuations is strongly affected by the trap aspect ratio so that future experiments should be able to detect them.



Magnetized spinor quantum gases

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Abstract:

Thermodynamic properties of a magnetized gas of identical atoms have been calculated for general spin F.[1] The mostly analytical results for *homogeneous* and *harmonically trapped* gases will be discussed. A semi–classical approximation is employed for the latter. A Bose gas with fixed magnetization is known to show two BEC phase transitions.[2, 3] Special attention is given to the temperature–dependent, non–linear *magnetic susceptibility* which is shown to reproduce, in the linear regime of the homogeneous gas, the magnetic susceptibility obtained in Ref.[4] within a random phase approximation of current–response functions. While explicit two–particle interactions have been neglected, our calculations properly account for transverse electromagnetic interactions.

References

[1] Benno Liebchen. Statik und Dynamik ultrakalter Spinor–Quantengase. Master's thesis, (Diplomarbeit, Supervisor: J. Bosse); Freie Universität Berlin, 2010.

[2] S. Yi Zhang, W. and L. You. *Phys. Rev. A*, 70:43611, 2004.

[3] S.-P. Parvis. Thermodynamic Properties of F=1 Spinor Bose–Einstein Condensates. Master's thesis, (Diplomarbeit, Supervisor: A. Pelster); Freie Universität Berlin, 2006.

[4] J. Bosse, K. N. Pathak, and G. S. Singh. Dynamics of Uniform Quantum Gases II: Magnetic Susceptibility. *Physica A: Statistical Mechanics and its Applications*, 389:1173–1177, 2010.

Collective Oscillation in Bose- Fermi Mixture

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Dynamics and Phase transitions in Bose Einstein condensates in Optical Lattice

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Abstract

The nature of phases in a optical lattice is studied in detail, using a collective coordinate approach. The discrete nonlinear Schrodinger equation is found to describe the dynamics well. The variational approach shows a rich phase structure, some of which are in close match with experiments. We identify the parameter regime where the system exhibits chaos.

Unusual Discrete Soliton and Breather Modes Collective Excitations in Bose-Einstein Condensates in the Efimov State

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Abstract

The dynamical evolution of collective excitations of the Bose-Einstein condensates in the Efimov state is studied and it shows very unusual behaviour. The dynamics if governed by discrete nonlinear Schrodinger equation (DNLS). We obtain the dynamical phase diagram of the system using variational method and direct numerical solutions of the DNLS equation. The discrete breather phase totally disappear in the Efimov state. Similarly, the soliton phase in the Efimov state exist only when the soliton line approaches the critical line in the phase diagram. When weak two-body interactions are added to the Efimov state, the discrete breather solutions reappear, but occupies a very small domain in the phase space. Likewise, in the Efimov region, the soliton as well as the discrete breather phase completely disappear if the signs of the two- and three-body interactions are opposite. The unusual behaviour of the collective mode excitations are signatures of the intriguing properties of the Efimov state.

Cavity Quantum Optomechanics of Ultracold Atoms in an Optical Lattice: Normal-Mode Splitting

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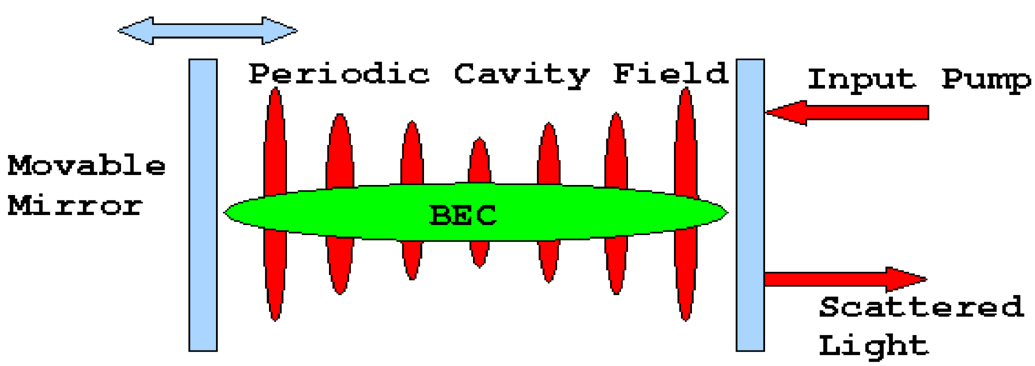
Abstract: We consider the dynamics of a movable mirror (cantilever) of a cavity coupled through radiation pressure to the light scattered from ultracold atoms in an optical lattice. Scattering from different atomic quantum states creates different quantum states of the scattered light, which can be distinguished by measurements of the displacement spectrum of the cantilever. We show that for large pump intensities the steady state displacement of the cantilever shows bistable behaviour. Due to atomic back-action, the displacement spectrum of the cantilever is modified and depends on the position of the condensate in the Brillouin zone. We further analyze the occurrence of splitting of the normal mode into three modes due to mixing of the mechanical motion with the fluctuations of the cavity field and the fluctuations of the condensate with finite atomic two-body interaction. The present system offers a novel scheme to coherently control ultracold atoms as well as cantilever dynamics.



Bosons in Optical Lattices

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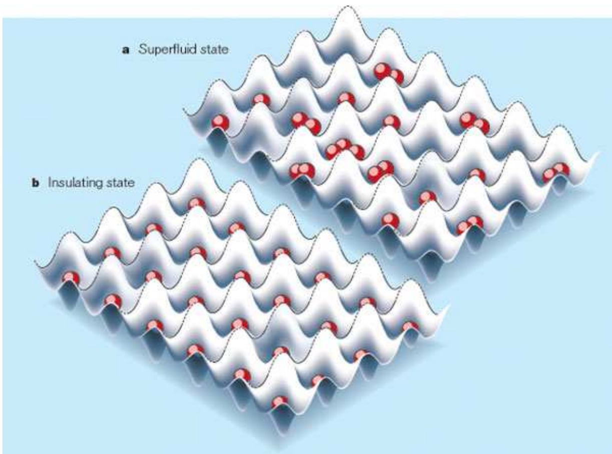
Systems of ultracold bosonic gases in optical lattices have recently become a popular research topic as they represent model systems for quantum phase transitions in solid-state physics with a yet unprecendented level of control. For a small laser strength the bosons can tunnel from site to site and explore the whole lattice. This leads to a superfluid state which is characterized by long-range correlations, a continuous excitation spectrum, and a finite compressiblity. In the opposite situation of a large laser strength the bosons can no longer tunnel to the neighboring sites, so the occupation number of the sites is fixed. This so-called Mott phase has no long-range correlation, shows a gap in the excitation spectrum and is nearly incompressible. It is of particular interest to determine how the location of the transition from the superfluid to the Mott phase depends on the respective system parameters. Usually, one assumes that the temperature in the experiments is so low that thermal effects are completely negligible. In that case the phase boundary has been calculated analytically within both a mean-field theory and a strong-coupling approach or numerically by Monte-Carlo simulations. Only recently, one has initiated some theoretical work to include thermal effects in a systematic way. However, until today, the temperature of the bosons in an optical lattice is not known. Therefore, more experimental and theoretical studies are needed which aim at designing a thermometer for these systems.

This motivates our investigations where we describe the quantum phase transition of spinless bosons in optical lattices within a Ginzburg-Landau theory. To this end the underlying effective action is derived from the microscopic Bose-Hubbard Hamiltonian by developing diagrammatic techniques for a resummed hopping expansion. Thus, this Ginzburg-Landau theory inaugurates a new approach for determining the properties of bosonic atoms in lattice systems. Already in second hopping order it exhibits a relative error of less than 3 % for the boundary between the superfluid and the Mott insulator phase of a three-dimensional cubic optical lattice when compared with the most recent results of Quantum Monte Carlo simulations. In addition, the Ginzburg-Landau theory also allows to calculate near-equilibrium as well as nonequilibrium quantities. Thus, our approach shows that, although comparable with numerical methods in terms of accuracy, the analytical Ginzburg-Landau theory presented here offers a much better qualitative understanding of the respective system properties.



Nonlinear Localised Solutions in the Spectrum Gap

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Abstract

Nonlinear localised excitations in the gap region of the spectra are important as these excitations avoid resonance with the linear spectra of the system and therefore do not decay into radiation. Gap solitons have already been experimentally observed in the BEC of rubidium atoms with periodic potential. We will show the existence of a new kind of excitations which we term as "gap compacton-like" within the gap of the linear spectrum of a system of coupled equations with nonlinear dispersion. The usefulness of such solutions in the context of BEC and other coupled systems will be discussed.

The Quantum Acousto-Optic Effect in Bose-Einstein Condensate

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Abstract

We investigate the interaction between a single mode light field and an elongated cigar shaped Bose-Einstein condensate (BEC), subject to a temporal modulation of the trap frequency in the tight confinement direction. Under appropriate conditions, the longitudinal sound like waves (Faraday waves) in the direction of weak confinement acts as a dynamic diffraction grating for the incident light field analogous to the acousto-optic effect in classical optics. The change in the refractive index due to the periodic modulation of the BEC density is responsible for the acousto-optic effect. The dynamics is characterised by Bragg scattering of light fom the matter wave Faraday grating and simultaneous Bragg scattering of the condensate atoms from the optical grating formed due to the interference between the incident light and the diffracted light fields. Varying the intensity of the incident laser beam we observe the transition from the acousto-optic effect regime to the atomic Bra gg scattering regime, where Rabi oscillations between two momentum levels of the atoms are observed. We show that the acousto-optic effect is reduced as the atomic interaction is increased.

The Amplitude Mode at the Superfluid-Mott Insulator Transition

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We study a two dimensional gas of repulsively interacting bosons in the presence of both an optical lattice and a trap using optical lattice modulation spectroscopy. The strongly interacting superfluid supports two types of low energy modes associated with the symmetry breaking at the phase transition: gapless phase (Goldstone) modes and gapped amplitude (Anderson-Higgs) modes. Both experimentally and in theoretical simulations lattice modulation spectroscopy shows an onset of absorption at a frequency associated with the amplitude mode gap, followed by a broad absorption peak at higher frequencies. From the simulations, we learn that energy is being absorbed by various amplitude modes, which inside a trap resemble the modes of a (gapped) drum. Our main results are: (1) despite coupling to the phase modes, modulation spectroscopy shows a sharp absorption onset at the frequency associated with the amplitude mode gap; (2) as we approach the Mott transition the gap softens and finally disappears at the transition point; (3) in the weak coupling regime, deep in the superfluid phase, the amplitude mode disappears.