Contents

Chapter 1

TALKS

1.1 Monday, July 15

DYNAMICS OF A ROTATING BOSE GAS

V. Bretin, F. Chevy, P. Rosenbuch, and J. Dalibard
Laboratoire Kastler Brossel, 24 rue Lhomond, 75005 Paris, France

We shall present recent experimental results concerning the dynamics of a harmonically confined Rb Bose gas when it is stirred by a small rotating anisotropic potential.

We will first address the region of critical rotation, where the stirring frequency is close to the trapping frequency. We identify two regimes: the regime of explosion where the cloud expands to infinity in one direction, and the regime where the condensate spirals out of the trap as a rigid body. The former is realized for a dilute cloud, and the latter for a condensate with the interparticle interaction exceeding a critical value. This constitutes a novel system in which repulsive interactions help in maintaining particles together [1].

We will then focus on the case where the stirring frequency is ∼0.7 the trapping frequency. In this case a single vortex is produced. By imaging the atoms in the longitudinal and transverse directions simultaneously, we observe the vortex line and show that it is rarely straight, but curved at the ends. We observe the dynamics of the vortex line up to 10 s after nucleation and we give its variation with temperature. We find that the shape of the vortex line is related to the z component of the angular momentum per particle, L_z.

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STRONGLY CORRELATED GROUND STATES IN DILUTE BOSE GASES: THEIR VARIETIES, ORIGINS AND SIGNATURES

Tin-Lun (Jason) Ho
Department of Physics, The Ohio State University, Columbus, Ohio, USA

We shall discuss a variety of strongly correlated ground states in dilute Bose gases created under different physical environment such as rotating traps and lattice potentials. Many novel ground states will emerge if spin degrees of freedom are released. We shall discuss the origins of these ground states and point out their key signatures.

BEYOND MEAN FIELD PHYSICS WITH BOSE-EINSTEIN CONDENSATES IN OPTICAL LATTICES

Immanuel Bloch[1,2], Markus Greiner[1,2], Olaf Mandel[1,2], Tim Rom[1,2], Artur Widera[1,2] and Theodor W. Hänsch[1,2]
[1] *Ludwig-Maximilians University of Munich, Schellingstr. 4/III, 80799 Munich, Germany*
[2] *Max-Planck-Institute for Quantum Optics, 85748 Garching, Germany*

A classical system cannot change configuration at absolute zero temperature. However, this is not true for its quantum mechanical counterpart. Here fundamental quantum fluctuations are able to induce a phase transition between two ground states as the relative strength of two competing terms in the underlying Hamiltonian is changed. In the talk I will present our results on such a quantum phase transition that occurs, when atoms from a Bose-Einstein condensate are loaded into a three-dimensional optical lattice potential. For low potential depths the atoms form a superfluid phase, in which each atom is spread out over the entire lattice, with perfect phase coherence across the lattice. For high potential depths the repulsive interactions between the atoms cause a transition to a Mott insulator phase. In this phase the atoms are localized to lattice sites with an exactly defined atom number per site, which leads to a loss of phase coherence. Recently we have also been able to observe that ultracold collisions between the atoms lead to a collapse and revival of the macroscopic wave function. With these experiments we are able to enter a new field of physics with ultracold quantum gases. Now interactions between atoms dominate the behavior of the many-body system, such that it cannot be described anymore by the usual theories for weakly interacting Bose gases. This novel quantum system offers the unique possibility to experimentally address fundamental questions of modern solid state physics, atomic physics and quantum optics.

EXCITATION SPECTRUM OF A BOSE-EINSTEIN CONDENSATE

J. Steinhauer, R. Ozeri, N. Katz and N. Davidson
Department of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

We report a measurement of the bulk excitation spectrum and the static structure factor of a Bose-Einstein condensate using Bragg spectroscopy. The excitation spectrum displays a linear phonon regime, as well as a parabolic single-particle regime. The linear regime provides an upper limit for the superfluid critical velocity, by the Landau criterion. The excitation spectrum and is found to agree well with the Bogoliubov spectrum in the local density approximation, even close to the long-wavelength limit of the region of applicability [1]. The momentum and energy of the phonons are also measured directly from a single time-of-flight image by computerized tomography [2]. We find that the same atoms that carry the momentum of the excitation also carry the excitation energy. The measured energy is in agreement with the Bogoliubov spectrum. Finally, the suppression of collisions of quasi-particles with ground state atoms within the condensate is measured at low momentum [3]. These collisions correspond to Baliaev damping of the excitations, in the previously unexplored regime of the continuous quasi-particle energy spectrum.

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COLLECTIVE OSCILLATION OF A TRAPPED 1D BOSE GAS

C. Menotti[1,2] and S. Stringari[1]
[1] *Dipartimento di Fisica, Università di Trento, and INFM, I-38050 Povo, Italy*
[2] *Dipartimento di Matematica e Fisica, Università Cattolica del Sacro Cuore, I-25121 Brescia, Italy*

Using the hydrodynamic equations of superfluids, we calculate the frequency of the collective oscillations of a Bose gas at zero temperature trapped in an elongated harmonic potential and show that it provides an useful indicator of the state of the system.

An analytic solution exists for the following 1D configurations: the *3D cigar*, where the condensate is Thomas-Fermi in the radial direction; the *1D mean field*, where due to tight confinement the motion in the radial direction is frozen; the *Tonks-Girardeau gas*, where strong correlations exist and the bosonic wavefunction can be mapped on a fermionic wavefunction. For the situations in between, we calculate the frequency using a sum rule approach.

Our procedure consists in calculating the equation of state for a system confined radially by a harmonic potential and uniform along the axial direction. We use the Gross-Pitaevskii theory to describe the mean-field regimes and the Lieb-Liniger theory to go beyond mean-field. We apply the local density approximation to include the harmonic trapping in the axial direction and identify the relevant combinations of the physical parameters governing the transition between the different regimes. Then we use the energy weighted and inverse energy weighted sum rules to determine the frequency of the lowest compressional mode.

The conditions of applicability of our method and the interplay between 3D and 1D effects are discussed. Finally, we compare briefly our results with the Quantum Monte-Carlo calculation of the ground state for interacting bosons in a harmonic trap [1].

1. see poster QUANTUM MONTECARLO STUDY OF THE 3D-1D CROSSOVER FOR A TRAPPED BOSE GAS, G.E. Astrakharchik and S. Giorgini

PHASE FLUCTUATIONS AND COHERENCE PROPERTIES OF BOSE-EINSTEIN CONDENSATES

J.J. Arlt[1], D. Hellweg[1], S. Dettmer[1], M. Kottke[1], T. Schulte[1], P. Ryytty[1], L. Cacciapuoti[1], K. Sengstock[2] and W. Ertmer[1]
[1] *Institut für Quantenoptik, Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*
[2] *Institut für Laserphysik, Universität Hamburg, Jungiusstr. 9, 20355 Hamburg, Germany*

Many of the most intriguing features of Bose-Einstein condensates (BEC) such as their superfluidity are linked to their coherence properties. Hence a thorough understanding of the macroscopic phase is essential for applications of BECs as source of coherent matter waves and for their use in interferometric measurements.

We present our results on the phase correlation properties of elongated BECs. It will be shown that the phase of a BEC is not necessarily spatially uniform but undergoes statistical fluctuations depending on the trapping parameters and ensemble temperature. In particular we have observed condensates with a phase coherence length smaller than the condensate size, i.e. so called quasicondensate.

For most of the measurements presented here, our method to detect phase fluctuations is based on ballistic expansion. We observe the occurrence of pronounced stripes in the density distribution depending on the experimental parameters. By varying the aspect ratio of our trap and the temperature of the ensemble, we observed a continuous transition from small to strong phase fluctuations. Our data confirm the theoretically predicted general behaviour of phase fluctuations in elongated BECs. In addition we show how the coherence length may be measured directly under these circumstances.

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1.2 Tuesday, July 16

PHASE COHERENCE LENGTH OF AN ELONGATED BOSE-CONDENSATE VIA BRAGG SPECTROSCOPY

F. Gerbier, S. Richard, J.H. Thywissen, M. Hugbart, P. Bouyer and A. Aspect
Groupe d'Optique Atomique, Laboratoire Charles Fabryde l'Institut d'Optique, UMRA 8501 du CNRS, Bât. 503,Campus universitaire d'Orsay, B.P. 147, F-91403 ORSAY CEDEX, FRANCE

As shown recently both theoretically [1] and experimentally [2],the correlation properties of Bose-Einstein condensates aresignificantly affected by the trap geometry. In cigar-shaped trapswith high aspect ratio, the coherence length is predicted [1] tobe smaller than the size of the sample because of thermalfluctuations of the condensate phase. Below a characteristictemperature T_ϕ, the latter are suppressed and phasecoherence extends across the whole sample.
In our experiment, we use Doppler-sensitive Bragg spectroscopy[3] to extract the velocity distribution. We release the trapbefore probing the BEC: this reduces the density significantlyenough to avoid the mean field broadening of the line [3], s-wavecollisions between the diffracted atoms and the parent BEC [4] andsuperradiant Rayleigh scattering [5]. However, a small amount ofthe release energy [6] is converted to an axial velocity field,which produces an extremely narrow resonance ($\sim$ 100 Hz).Phase fluctuations on a length scale L_ϕ correspond to afluctuating velocity field with a width $v_\phi \sim \hbar/ML_\phi$, that broadens the resonance expected for a perfectlycoherent condensate. We will present our efforts to measurequantitatively the coherence length along the long axis of trapswith aspect ratios between 70 and 200.

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EXCHANGE EFFECTS AND INTERNAL WAVES IN NONDEGENERATE AND DEGENERATE GASES

Leonid Levitov[1] and Mehmet Oktel[2]
[1] *Physics Department, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA-02139, USA*
[2] *Physics Department, Ohio State University, 174 West 18 Avenue, Columbus, OH-43210, USA*

In a gas of nondegenerate particles, at temperatures in the cold collision range, the interaction between the atoms can be described by a self-consistent dynamical mean field. For atoms with several internal states, this field couples to the internal "spin" degrees of freedom. As a result, exchange in a Boltzmann gas of bosons with several internal states leads to collective transport of internal polarization. The internal dynamics can be understood as Larmor precession in the presence of a torque induced by atoms on each other via exchange coupling [1].

In a recent experiment by Lewandowski et al. [2] collective waves of internal state polarization in a cold magnetically trapped Rb vapor were observed by a new spatially resolved technique. A generalized Bloch equation that includes interatomic exchange effects as well as orbital motion in the gas is derived and used to interpret the experiment [2] as an excitation of a collective wave of internal state polarization. It is predicted that exchange leads to formation of domains in which precession frequencies are synchronized [3]. The decay of the spin waves is accounted for by the collisionless Landau damping theory extended to confined geometry.

These effects become more interesting at $T < T_{\mathrm{BEC}}$, leading to an interplay between the Rabi and internal Josephson effects. Based on a microscopic transport equation for the density matrix, we map the problem onto a problem of precession of two coupled classical spins. In the absence of an external excitation field our results agree with the theory for the density induced frequency shifts in atomic clocks. In the presence of the external field, the internal Josephson effect takes place in a condensed Bose gas as well as in a noncondensed gas. The crossover from Rabi oscillations to the Josephson oscillations as a function of interaction strength is studied in detail [4].

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RECENT EXPERIMENTS IN BOSE-EINSTEIN CONDENSATION AT JILA

Eric Cornell
[1] *JILA, National Institute of Standards and Technology and the University of Colorado, Boulder, CO, USA*

I will present an overview of recent experimental work at JILA, touching on spin-waves and atom-guiding but concentrating mostly on recent observations of distorted vortex lattices and on the recent observation (in the lab of Carl Wieman) of coherent oscillations between atoms and molecules.

DYNAMICS OF AN ISOLATED WEAKLY INTERACTING BOSE GAS

Krzysztof Góral[1], Mariusz Gajda[2], and Kazimierz Rzążewski[1]
[1] *Center for Theoretical Physics,* [2] *Institute of Physics, Polish Academy of Sciences,*
Aleja Lotników 32/46, 02-668 Warsaw, Poland

Understanding the quantum behavior of a Bose-Einstein condensate at non-zero temperatures remains a challenge. We present a simple and convenient technique describing the condensate in dynamical equilibrium with the thermal cloud [1,2], at temperatures close to the critical one. We show that the whole isolated system may be viewed as a single 'classical field' undergoing nonlinear dynamics leading to a steady state. The condensate is defined is defined as the dominant term in the spectral decomposition of the time-averaged single-particle density matrix. Two cases are discussed: the box with periodic boundary conditions and the realistic case of a spherically symmetric harmonic trap. In our procedure it is the observation process and the finite detection time that allow for splitting the system into the condensate and the thermal cloud. The method may be used to model the impact of thermal fluctuations on the dynamical processes with the condensate, such as solitons or vortices. The next step in going beyond the approximations employed in our model is the estimation of the influence of quantum corrections to the 'classical fields', in particular the study of the corresponding time scales.

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FESHBACH RESONANCES IN BOSONIC AND FERMIONIC LITHIUM: SOLITONS TO SUPERFLUIDS

Randall Hulet, Kevin Strecker, Guthrie Partridge, Ying-Cheng Chen
Rice University, Dept. of Physics and Astronomy, MS-61 Houston, Texas, USA

We have performed experiments with quantum gases of the bosonic and fermionic isotopes of lithium and their mixture [1]. Both isotopes exhibit large Feshbach resonances between 700-800 G in non-magnetically trappable states. Therefore, following evaporative cooling in a magnetic trap, the atoms are transferred to an optical trap made with a single focused infrared Nd-YAG laser for radial confinement and two doubled Nd-YAG beams as axial end-caps. We have used the Feshbach resonance in the bosonic isotope, ^{7}Li, to make a large Bose-Einstein condensate with repulsive interactions [2]. Up to 3×10^5 condensate atoms were produced. By reducing the magnetic field, the interactions were made attractive and a train of up to 10 bright atomic solitons were formed. The solitons were launched into the 1D harmonic optical potential by creating them on the side of the potential and switching off the axial end caps. The solitons were observed to maintain their shape without spreading for times of up to 3 s and over distances of 1 mm. The relative separation between solitons in the train oscillates at twice the harmonic trapping frequency. This indicates strong, short-range repulsive interactions, which suggests that adjacent solitions in the train are formed with a relative phase difference of π. This is confirmed by direct solution of the Gross-Pitaevskii equation [3]. The formation of the soliton train can be explained by a modulational instability seeded by phase fluctuations [3]. A similar experiment with ^{7}Li was performed at the ENS in Paris where single bright solitons were formed [4]. A soliton train was not observed in this experiment, however, perhaps because the initial number of condensate atoms was 10 times smaller.

The Feshbach resonance in the fermionic isotope, ^6Li, may enable the creation of a gaseous superfluid state. We are currently pursuing this goal.

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RESONANCE SUPERFLUIDITY IN DILUTE ATOMIC GASES

Murray Holland, Marilu Chiofalo, Servaas Kokkelmans, and Josh Milstein
JILA, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

The ability to tune the interactions of dilute atomic gases by means of a Feshbach resonance has opened up a wide range of exciting new physics, calling for a correct description of the resonant behavior. Starting from a model Hamiltonian [1,2] which incorporates the resonance through the introduction of a molecular degree of freedom, we have developed a field-theoretic model which allows for the emergence of Cooper pairs. By retaining the pairing field, we are forced to deal with problems of ultraviolet divergences, which must be remedied through a proper procedure of renormalization. This renormalization, however, has to not only remove the large wavenumber divergences, but must also reproduce the correct microscopic physics of the resonance. We, therefore, build our renormalization procedure [3] by explicitly relating the bare interactions U and g, describing the 2-body and resonant interactions, respectively, with the full scattering T-matrix describing the Feshbach resonance. With this renormalized model in hand, we have been able to describe a wide array of problems in the physics of atomic gases, from postulating a simple way to detect the superfluid transition by a direct density measurement [4] to predicting an enhanced value of Tc close to the resonance [2,5], not far from experimentally achievable temperatures. Perhaps most important is the recent agreement with experiment on Bose condensed rubidium-85 describing the formation of a molecular condensate [6,7].

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1.3 Wednesday, July 17

THE OBSERVATION OF A SUPERFLUID GYROSCOPE

E. Hodby, S.A. Hopkins, G.Hechenblaikner, N. Smith and C.J. Foot
[1] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*

We have observed a superfluid gyroscope in a dilute gas Bose-Einstein Condensate - an effect described theoretically in [1]. In the experiment we first need to produce a single, centred vortex line on the z axis of a condensate of Rb-87 atoms in a TOP trap [2]. We then excite the scissors mode oscillations (in the xz-plane) [3] by a sudden rotation of the trapping potential through a small angle. A condensate with a vortex possesses angular momentum and this causes the plane of oscillation of the scissors mode to precess around the axis of the vortex. From measurements of this precession rate we deduced the angular momentum associated with the vortex line and found that it is comparable to the value of $\hbar$ per particle predicted for a superfluid. The motion of the vortex core relative to the condensate during the gyroscope motion is also of interest and will be discussed.

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THE TRANSITION TEMPERATURE OF THE DILUTE INTERACTING BOSE GAS

Jean-Paul Blaizot
Service de Physique Théorique, CEA/DSM Saclay,
91191 Gif-sur-Yvette cedex, France

The effect of weak repulsive interactions on the transition temperature of the dilute Bose gas has remained until recently the subject of controversies. The difficulty arises from the fact that, although the interaction can be arbitrarily weak, standard weak couling techniques like perturbation theory cannot be applied because they lead to infrared divergent results. In this talk I shall show how this difficulty can be overcome and review recent studies which have shown that the transition temperature increases linearly with the scattering length a, with non universal corrections of order $a^2 \ln a$. The various techniques used to determine the coefficient of the linear term will be discussed.

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RECENT WORK ON QUANTUM-DEGENERATE ALKALI GASES AT MIT

Wolfgang Ketterle
Research Laboratory for Electronics, MIT-Harvard Center for Ultracold Atoms, and Department of Physics, Massachusetts Institute of Technology, Room 26-243, 77 Massachusetts Ave., Cambridge, MA 02139-4307, USA

My talk will summarize recent progress in different areas.

(1) Using optical tweezers, condensates were transported by more than 40 cm into a separate science chamber and loaded into a magnetic waveguide created by a microchip.

(2) Vortices were created using topological phases.

(3) Sympathetic cooling of lithium-6 by sodium resulted in a stable mixture of a degenerate Fermi sea and a Bose-Einstein condensate. A Feshbach resonance between two hyperfine states of lithium has been observed.

(4) High-gain four wave mixing was used to generate pair-correlated atomic beams.

(5) A new regime of superradiance was observed with rubidium BECs.

DYNAMICS OF TRAPPED BOSE GASES AT FINITE TEMPERATURES

E. Zaremba
Department of Physics, Queen's University, Kingston, Ontario, Canada K7L 3N6

A description of the dynamical behaviour of a trapped Bose-condensed gas at finite temperatures requires a consistent theory of the condensate order parameter and the noncondensed thermal component. In our formulation of such a theory [1], the dynamics of the condensate is described by a generalized Gross-Pitaevskii (GP) equation while a semiclassical kinetic equation is used to describe the thermal cloud. The two equations are coupled by mean fields as well as collisions that transfer atoms between the two components. This formulation can in principle provide a description of the dynamics from the collisionless to the hydrodynamic regimes.

To solve these equations we have developed a numerical procedure [2] in which the 3D GP equation is evolved in time using a FFT split-operator technique, while the kinetic equation is represented by an N-particle classical simulation. Collisions between atoms are treated by means of a Monte-Carlo procedure. By establishing some initial nonequilibrium configuration, the full dynamical behaviour of the condensate and thermal cloud can be followed in time.

We have recently applied this procedure to analyze several situations of experimental interest. In particular, we have been able to explain the observed behaviour of scissors modes [3] as studied by the Oxford group, the collective modes in early JILA experiments [4], and more recently, the transverse breathing mode as studied by the ENS group [5]. In all cases, we obtain quantitative agreement with experiment. In this talk I will summarize these applications as well as other dynamical simulations we have performed.

†This work was done in collaboration with Brian Jackson.

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PROOF OF BOSE-EINSTEIN CONDENSATION FOR DILUTE TRAPPED GASES

Elliott H. Lieb and Robert Seiringer
Department of Physics, Jadwin Hall, Princeton University,
P.O. Box 708, Princeton, New Jersey 08544, USA

The ground state of bosonic atoms in a trap has been shown experimentally to display Bose-Einstein condensation (BEC). We prove this fact theoretically for bosons with two-body repulsive interaction potentials in the dilute limit, starting from the basic Schrödinger equation; the condensation is 100% into the state that minimizes the Gross-Pitaevskii energy functional. This is the first rigorous proof of BEC in a physically realistic, continuum model.

ADIABATIC AND NON-ADIABATIC LOADING OF BOSE-EINSTEIN CONDENSATES INTO ONE-DIMENSIONAL OPTICAL LATTICES

O. Morsch, M. Cristiani, J.H. Müller, D. Ciampini and E. Arimondo
INFM, Dipartimento di Fisica E.Fermi, Università di Pisa,
Via F. Buonarroti 2 , I-56127 Pisa, Italy

We present experimental results on the properties of Bose-Einstein condensates in optical lattices. From the free expansion of a condensate adiabatically loaded into a 1D lattice, we have calculated the increase in chemical potential due to the presence of the periodic potential. For non-adiabatic loading, we have studied the response of the condensate to the sudden switch-on of the lattice, leading to radial oscillations and a complex behaviour of the contrast of the interference pattern after a time-of-flight.

DYNAMICS OF A BOSE-EINSTEIN CONDENSATE IN A 1D OPTICAL LATTICE

C. Fort, F. S. Cataliotti, L. Fallani, F. Ferlaino, P. Maddaloni, and M. Inguscio
LENS, Dipartimento di Fisica, Università di Firenze and INFM,
via Nello Carrara 1, I-50019 Sesto Fiorentino (Firenze), Italy

We present experiments performed on the dynamical properties of an array of harmonically trapped Bose-Einstein condensates produced in presence of a 1D optical lattice. Both dipole and quadrupole mode frequencies were studied as a function of the optical well depth evidencing strong modification of the dynamics along the axes of the periodic potential due to tunnelling between adjacent wells. We also demonstrate the equivalence between the linear array of BECs and a linear array of Josephson Junction giving a direct measurement of the critical atomic current in our system.

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1.4 Thursday, July 18

ULTRA-COLD MIXTURES OF BOSE AND FERMI LITHIUM GASES

L. Khaykovich, F. Schreck, G. Ferrari, T. Bourdel,
J. Cubizolles, L. Carr, Y. Castin, and C. Salomon
Laboratoire Kastler Brossel, ENS, 24 rue Lhomond, 75231 Paris CEDEX 05, France

We report on recent experiments on ultra-cold mixtures of Bose and Fermi gases confined in magnetic or optical traps. First, we have produced a quasi-pure ^{7}Li Bose-Einstein condensate immersed in a ^{6}Li Fermi sea at a common temperature of $0.28\,\mu\mathrm{K} \simeq 0.2(1)\,T_\mathrm{C} = 0.2(1)\,T_\mathrm{F}$ where T_C is the BEC critical temperature and T_F the Fermi temperature [1]. Behaving as an ideal gas in the radial trap dimension, the condensate has a one-dimensional character. This mixture of fermionic and bosonic quantum system opens interesting possibilities for the study of phase separation, the influence of the superfluidity of the Bose system on the Fermi degeneracy and of the cooling limits of the Bose-Fermi mixed gas.

Second, the large effective attractive interaction between ^{6}Li $|F = 1/2, m_F = +1/2\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ makes this atom a good candidate for searching for BCS pairing if the temperature can be made sufficiently low [2]. In particular it has been recently predicted that near a Feshbach resonance the BCS transition temperature could become as high as $0.5\,T_F$ [3]. In the ^{6}Li $|F = 1/2, m_F = \pm 1/2 >$ spin states, such a Feshbach resonance occurs for a magnetic field near 810 Gauss [2,4]. As these states cannot be trapped magnetically, we have constructed a far detuned crossed dipole trap in which all hyperfine states of both lithium isotopes can be confined in an adjustable external magnetic field.

As a first step, we have observed a Feshbach resonance in ^{7}Li predicted at 725 Gauss [4]. Using this resonance we magnetically tuned the effective interactions in a ^{7}Li Bose-Einstein condensate from repulsive to attractive and produced bright matter-wave solitons [5,6,7]. Soliton propagation in a one-dimensional optical waveguide without dispersion over a distance of 1.1 mm is observed. A simple theoretical model explains the stability region of the soliton. Progress on optical trapping of ^{6}Li fermion mixture will be reported.

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SCATTERING ON A BOSE-EINSTEIN CONDENSATE

Uffe V. Poulsen and Klaus Mølmer
Department of Physics and Astronomy, University of Aarhus,
DK 8000 Århus C., Denmark

Identical particle scattering from an atomic sample has been proposed as a means to determine the condensate fraction and various many-body properties in superfluid Helium-4 and in dilute systems [1]. Particles, which are injected into a condensate, propagate as quasi-particles through the medium and emerge on either side of the condensate in reflected and transmitted components. A Bogoliubov approach is presented to this problem, and reflection and transmission coefficients are determined as functions of the incident momentum. We compare the problem with normal potential scattering, and we identify a number of genuine many-body features of the process. In addition to an oscillatory dependence of the transmission probability on incident momentum, known also for normal barrier transmission, we find a rather wide momentum range with non-negligible transmission probability where the transmission times are negative, i.e., the transmitted peak of the atomic wave packet appears *before* the incident peak arrives. For a general discussion of superluminal propagation and negative time-delays, see [2].

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BOSE-EINSTEIN CONDENSATES IN PERIODIC OPTICAL POTENTIALS

Steven L. Rolston
National Institute of Standards and Technology,
Atomic Physics Division, Gaithersburg, MD 20899-8424, USA.

The narrow momentum spread and coherence of a BEC makes it an ideal starting point for investigating atomic dynamics in periodic potentials. Using adiabatic techniques, it is possible to load the atoms into a single well-defined quasimomentum, in an essentially defect-free periodic potential. I will describe a series of experiments in this model solid state system, including effects of accelerations and controlled excitations to higher lying bands. These can all be understood as single particle phenomena, and are performed with a sodium BEC in a weak magnetic trap, where the effects of mean field interactions are negligible. When atom-atom interactions are included, quasimomentum is no longer a good quantum number, and the phase of the wave function across the lattice may vary in ways dependent on the time scales for loading the lattice. I will discuss experiments that look at such effects, including transport in the lattice.

Atoms trapped in optical lattices have been proposed as a basis for a quantum computer, and a BEC is an ideal source of atoms because it is easy to load into the vibrational ground state of the lattice. One of the challenges for quantum computation is balancing the need for tight confinement (to create high densities and strong interactions) with large spacings (for individual addressing of the qubits). To this end we have demonstrated how to have the best of both worlds, by loading atoms into every nth plane of an optical lattice (in 1 and 3-D). This was done with a Rb BEC adiabatically loaded into a "superlattice" with two periods in a ratio of exactly 3:1. Using both atomic diffraction and optical Bragg diffraction we confirm this patterned loading. This system, with loaded sites neighboring empty sites, should be ideal to look for the inhibition of tunneling due to the mean field ("macroscopic quantum self-trapping").

This work was done in collaboration with A. Browaeys, J. Denschlag, H. Haeffner, C. McKenzie, B. Laburthe-Tolra, T. Porto, K. K. Helmerson, and W. Phillips, and is partially supported by ONR, NASA, and ARDA-NSA.

Chapter 2

POSTERS

PHOTOIONIZATION OF ULTRACOLD AND QUANTUM DEGENERATE Rb ATOMS

D. Ciampini, M. Anderlini, J.H. Müller, O. Morsch,
E. Courtade, F. Fuso and E. Arimondo
*INFM, Dipartimento di Fisica E.Fermi, Università di Pisa,
Via F. Buonarroti 2 , I-56127 Pisa, Italy*

We irradiated magnetically trapped Rb condensates with pulsed and continuous laser radiation above the 2-photon or 1-photon ionization threshold. For the measurements on magneto-optically trapped samples traditional trap loss spectroscopy [1] was applied to determine the ionization rate and extract cross section data. For the purely magnetically trapped condensates shadow imaging of the clouds after interaction with the ionizing radiation gave access not only to the number of remaining ground state atoms but also to their density distribution and temperature. Apart from losses of atoms from the trap we observe drastic modifications of the density distribution and transfer to different magnetic sublevels. Relevant mechanisms like dipole forces, induced Raman scattering and possibly interaction of ionization products with the coherent neutral background will be discussed at the poster.

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FORMATION OF A MATTER-WAVE SOLITON

T. Bourdel[1], L. Khaykovich[1], F. Schreck[1], G. Ferrari[2], J. Cubizolles[1], and C. Salomon[1]
[1] *Laboratoire Kastler Brossel, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris, France*
[2] *LENS-INFM, Largo E. Fermi 2, Firenze 50125, Italy*

Solitons are localized wave packets that travel over long distances without changing their size and shape. They are formed when spreading (dispersion) that tends to increase their size is compensated by nonlinear effects. A Bose-Einstein Condensate (BEC) (a macroscopic matter-wave), with attractive mean-field interaction and subject to two-dimensional (2D) trapping potential, supports bright solitons as was shown theoretically by a number of authors [1]. For repulsive interactions, only *gray* or *dark* solitons has been realized in BEC [2]. We report the first realization of a matter-wave bright soliton. The soliton is produced from ^{7}Li BEC formed in the absolute ground state ($|F = 1, m_F = 1\rangle$) and confined in a far detuned crossed dipole trap. A Feshbach resonance [3] around 725 G allows us to effectively tune the scattering length during the experiment. First, BEC with repulsive interactions is obtained by evaporation, performed by lowering the optical potential. The scattering length is set large and positive ($a = +2.1$ nm) at this stage to make evaporation possible. Then, the sign of the scattering length is changed to negative ($a = -0.2$ nm) and the atomic wave packet is released in a 1D optical guide. We observe the propagation of the soliton over a distance of 1.3 mm without dispersion. We develop a simple theoretical model to investigate the stability region of the soliton and find it to be in excellent agreement with the experiment [4]. In a similar experiment, trains of solitons were formed [5].

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ENHANCEMENT OF THE SCISSORS MODE OF AN EXPANDING BOSE-EINSTEIN CONDENSATE

M. Modugno[1], G. Modugno[1], G. Roati[12], C. Fort[1], F. S. Cataliotti[1] and M. Inguscio[1]
[1] *LENS and Dipartimento di Fisica, Università di Firenze*
Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy
[2] *Dipartimento di Fisica, Università di Trento, 38050 Povo, Italy*

We investigate theoretically and experimentally the consequences of the irrotational flow of a Bose-Einstein condensate on the expansion of the scissors mode. Despite the non trivial character of the expansion of a superfluid, we find that asymptotically the mode is still characterized by a sinusoidal behavior, which depends linearly on the initial amplitude and angular velocity, resulting in an enhancement of the final amplitude. We also demonstrate a new experimental tool for exciting the scissors mode in an elongated magneto-static trap, which exploits the particular shape of the magnetic field at the trap center. This allows us to investigate the dramatic implications of the irrotationality and the enhancement effects of the mode amplitude during the expansion. We also study the dynamics of a two BEC mixture of ^{41}K and ^{87}Rb, where off-axis collisions between the two interacting condensates induce scissors-like oscillation.

EXPLORING PHYSICS USING TRANSPORTED BOSE-EINSTEIN CONDENSATES

A. P. Chikkatur, A.E. Leanhardt, Y. Shin, D. Kielpinski, E. Tsikata, T. L. Gustavson, D. E. Pritchard and W. Ketterle
Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Conventional condensate production techniques severely limit optical and mechanical access for experiments due to the many laser beams and magnetic coils needed to create BECs. We have demonstrated an application of optical tweezers that transfers Bose condensates of over 2 million atoms over distances of 40 cm with a precision of a few micrometers[1]. This new apparatus separates the region of condensate production from that used for scientific studies.

In this new apparatus, we have performed the first experiments on propagation of BECs in magnetic waveguides. BECs were transported with using optical tweezers, transferred into a magnetic trap microfabricated on a silicon substrate, and then released into a single-wire magnetic waveguide[2]. We observed single-mode (excitation-less) condensate propagation along homogeneous segments of the waveguide. Transverse excitations were created in condensates as they propagated through perturbations in the guiding potential, resulting from geometric deformations of the current carrying wires. In addition, the condensate was observed to fragment along its axis when they were brought closer to the microchip.

We have created a continuous source of Bose-Einstein condensed atoms by periodically replenishing a condensate held in an optical dipole trap with new condensates delivered using optical tweezers[3]. The source contained more than 1×10^6 atoms at all times, raising the possibility of realizing a continuous atom laser.

In the magnetic microtrap, we have imprinted vortices using a topological phases. Condensates were transported in either $|F = 1, m_F = -1\rangle$ or $|F = 2, m_F = +2\rangle$ hyperfine state and then transferred into a Ioffe-Pritichard type magnetic trap produced by wires on the atom chip. By adiabatically inverting the magnetic bias field, we transformed condensates from a non-rotating state into a rotating state with angular momentum per particle of $-2m_F\hbar$[4]. We experimentally measured this angular momentum using surface wave spectroscopy[5].

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HYDRODYNAMIC MODES IN DENSE TRAPPED ULTRACOLD GASES

R. Combescot and X. Leyronas
Laboratoire de Physique Statistique, Ecole Normale Supérieure, Paris, France

Although most of the recent work on ultracold gases [1] has been dealing with dilute situations, it is of great interest to explore the dense gas regime where scattering length and interparticle distance are comparable. This would lead to physical systems which are very simple examples of strongly interacting systems. We show [2] that the experimental determination of the mode frequencies of trapped gases in the hydrodynamic regime allows to obtain quite directly the equation of state of a dense gas or equivalently the dependence $\mu(n)$ of the chemical potential on density.

We consider the case of a gas trapped in a 3D isotropic harmonic trap $V(r)$ with frequency Ω, although various generalizations are possible. A mode with frequency $\omega = \nu\Omega$ is characterized by a density fluctuation $n_1(\mathbf{r})$. Making the change of variable $n_1(\mathbf{r}) = (\partial\mu/\partial n_0)^{-1} r^l v(r) Y_{lm}$, we obtain for the mode the following equation:

$$rv'' + [2(l+1) + rL'(r)]v' - (\nu^2 - l)L'(r)v = 0 \tag{2.1}$$

Here $L(r) = \ln(n_0(r))$ where the equilibrium density of the trapped gas $n_0(r)$ satisfies $\mu(n_0(r)) + V(r) = Cte$. It is easily seen that only the normalized equilibrium density $\bar{n}(r) \equiv n(r)/n(0)$ and the normalized local chemical potential $\bar{\mu}(r) \equiv \mu(n(r))\mu(n(0))$ are relevant for the mode frequency. We have investigated a large class of models for the equation of state, defined parametrically by $\bar{n} = (1-y)^p \exp[\Sigma_n r_n y^n]$ and $\bar{\mu} = 1 - y^{2/\alpha}$. For the parameters $r_n = 0$ and the parameters p and α free, we find for the complete spectrum:

$$\frac{\omega^2}{\Omega^2} = l + \frac{\alpha}{p}\, n\,(n + p + \frac{2l+1}{\alpha}) \tag{2.2}$$

the solution being polynomials in the variable y. For the case $r_n \neq 0$ the solutions are very rapidly converging series ('quasipolynomials') and the mode frequencies are obtained essentially by finding the roots of some polynomials.

This very large class of models with essentially analytical solutions can be used to describe any physical $\mu(n)$ and to obtain readily the spectrum. We have checked on the case of a Fermi gas, with the interaction described by the Hartree approximation, that the simple model with only the two parameters p and α gives already to an excellent precision the lowest frequency modes. This procedure can be inverted to obtain $\mu(n)$ from the experimental knowledge of the mode frequencies. For example $\mu(n)$ can be obtained by knowing the lowest monopole mode frequency as a function of particle number in the trap.

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SCISSORS MODE IN A ROTATING BOSE-EINSTEIN CONDENSATE

Marco Cozzini[1] and Sandro Stringari[1],
Vincent Bretin[2], Peter Rosenbusch[2] and Jean Dalibard[2]
[1] *Dipartimento di Fisica, Università di Trento and INFM, I-38050 Povo, Italy*
[2] *Laboratoire Kastler Brossel, 24 rue Lhomond, 75005 Paris, France*

A Bose-Einstein condensate rotating at high angular velocity exhibits spontaneous rotational symmetry breaking as a consequence of two-body interactions [1]. In the presence of a slightly deformed rotating trap ($\epsilon = (\omega_x^2 - \omega_y^2)/(\omega_x^2 + \omega_y^2) \ll 1$, where ω_x and ω_y are the trapping frequencies in the plane of rotation) the symmetry breaking shows up in the occurrence of a soft oscillating rotation (scissors mode).

The frequency of the scissors mode is calculated analytically starting from the hydrodynamic equations of superfluids and is predicted to vanish like $\sqrt{\epsilon}$ in the rotating frame. The mode is produced experimentally by ramping up the angular velocity of the rotating trap in a quasi-adiabatic way and its frequency is measured by imaging the angle of the principal axis of the condensate in the plane of rotation as a function of time.

The experiment well confirms the predictions of theory for the dependence of the frequency on the deformation parameter of the trap, as well as for the oscillating behaviour exhibited by the internal shape of the condensate.

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STUDY OF OPTICAL LATTICE LOADING USING THE HYBRID VARIATIONAL METHOD

Mark Edwards[1,2] and Charles W. Clark[2]
[1] *Georgia Southern University, Fair Road, Statesboro, Georgia, USA*
[2] *NIST, 100 Bureau Drive, Gaithersburg, Maryland, USA*

We study the loading of a one–dimensional optical lattice from a Bose–condensed sample of neutral atoms assuming the validity of the Gross–Pitaevskii (GP) equation. Approximate solutions of the GP equation are provided by a variational method in which the trial wavefunction is allowed any form along the direction of the lattice and is assumed to be gaussian in the transverse direction. We study the extent to which the ground state of the lattice wells are occupied for various types of lattice turn on. We have also investigated the conditions of adiabaticity under these conditions.

PHASE COHERENCE OF AN ATOM LASER

M. Köhl and T. Esslinger
Institute for Quantum Electronics, ETH Zrich, CH-8093 Zrich, Switzerland

We present the measurement of the temporal phase coherence of an atom laser beam [1]. The beam is extracted from a rubidium 87 Bose-Einstein condensate and reflected from a potential barrier. This results in a standing matter wave structure at the turning point of the atomic trajectory. Using a novel magnetic resonance imaging method we can observe the matter wave interference with a spatial resolution of 65 nm. From the contrast of the interference pattern we have deduced an energy width of the atom laser beam of 700 Hz, which is Fourier limited by the duration of output coupling and well below the mean-field energy of the condensate. This measurement gives an upper limit for temporal phase fluctuations in the Bose-Einstein condensate.

We further report on a quantitative study of the growth process of rubidium 87 Bose-Einstein condensates. By continuous evaporative cooling we directly control the thermal cloud from which the condensate grows. We compare the experimental data with results of a theoretical model based on quantum kinetic theory [3]. We find quantitative agreement with theory for the situation of strong cooling whereas in the weak cooling regime a distinctly different behavior is found in the experiment.

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SHOCK WAVE LIKE SPIN OSCILLATIONS IN AN ULTRACOLD GAS

Jean-Noël Fuchs[1], Dimitri Gangardt[1,2] and Franck Laloë[1]
[1] *LKB, Département de Physique de l'ENS, 24 rue Lhomond, 75005 Paris, France*
[2] *Departement of physics, Technion, 32000 Haifa, Israel*

We consider the experimental situation of Lewandowski et al. [1] where a large longitudinal (pseudo) spin oscillation is created in an ultracold (non-condensed) Bose gas. A numerical simulation of the kinetic equation, which we used in Ref. [2], shows that the evolution of the system is sudden and that it does not remain close to local equilibrium (analogous, in this sense, to a shock wave). Therefore the non-linearity of the kinetic equation is an essential feature of this system and hydrodynamic-type equations are not valid. Comparison with other approaches [3] is given.

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STABILITY AND PHASE COHERENCE OF TRAPPED 1D BOSE GASES

D.M. Gangardt[1] and G.V. Shlyapnikov[1,2,3]
[1] *Laboratoire Kastler-Brossel, Ecole Normale Supérieure,*
24 rue Lhomond, F-75231, Cedex 05, Paris, France
[2] *FOM Institute for Atomic and Molecular Physics,*
Kruislaan 407, 1098 SJ Amsterdam, The Netherlands
[3] *Russian Research Center, Kurchatov Institute,*
Kurchatov Square, 123182 Moscow, Russia

The stability and phase coherence of 1D trapped Bose gases in the weakly interacting Gross-Pitaevskii (GP) regime, strongly interacting Tonks-Girardeau (TG) regime, and in between is discussed. Various local density–density correlators responsible for the rates of inelastic decay processes are calculated and it is found that 3-body recombination is strongly suppressed in the TG and intermediate regimes. This is especially promising for achieving these regimes at a large number of particles. The long distance behavior of the single-particle correlation function is calculated using the recently proposed hydrodynamic approach based on the local density approximation in the presence of a trapping potential. Our results show that the vacuum fluctuations of the phase become important upon the departure from the GP towards the TG regime. The zero-temperature phase coherence length becomes smaller than the Thomas-Fermi axial size of the sample, unless the gas is deeply in the GP regime.

SIMULATING SPIN LATTICES WITH COLD ATOMS IN OPTICAL LATTICES

J. J. García-Ripoll and J. I. Cirac
Max-Plank-Institut für Quantenoptik, Hans-Kopfermann-Str. 1,
Garching b. München, D-85748, Germany

In this work we show that an ensemble of cold atoms placed in an optical lattice [1] interacts with an effective Hamiltonian which corresponds to either the Heisenberg or the Ising model for $S = 1/2$ spins.

In the case of the Ising model we show that it is possible to create entangled states of maximal connectivity and persistence, as those described in [2], and that this can be done using current setups with great fidelity.

We also demonstrate that, with some technical improvement of current experiments, this ensemble of atoms may be used to perform general quantum computing, the local gates being provided by lasers or magnetic fields, and the nonlocal gates being built using the techniques mentioned above.

Finally, using atomic species with different interaction constants, these systems may be used to simulate ferromagnetic or antiferromagnetic spin lattices, providing us with a highly tunable instrument with which to generate spin waves, spin liquids and excitations with fractional statistics [3].

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THE NUCLEATION AND GROWTH OF VORTEX LATTICES

A. A. Penckwitt[1], R. J. Ballagh[1], C. W. Gardiner[2]
[1] *Department of Physics, University of Otago, Dunedin, New Zealand*
[2] *SCHOOL OF Chemical and Physical Sciences, Victoria University of Wellington, New Zealand*

Recent experimental observations of vortex lattices have raised important questions on the mechanisms of vortex formation, particularly the role of the thermal cloud. We give a simple unified treatment of vortex nucleation and vortex lattice formation based on quantum kinetic theory. We assume a thermal cloud with fixed chemical potential, temperature and angular velocity, and obtain a vortex growth equation which has similarities to the Gross Pitaevskii equation, but includes additional terms describing the collisional interchange between the thermal cloud and the condensate. We have used this equation to simulate both a condensate stirred with a rotating trap potential, and the formation of a lattice from a pure thermal cloud. A typical example of the condensate evolution in the latter case is shown as a sequence of condensate density plots in the figure. This evolution has three distinct phases: the arrival of an imperfect ring of vortices from infinity; the penetration of a number of these vortices into the dense condensate region; the shedding of further vortices and arrangement into a regular lattice. We give an analytic treatment of the first phase, by calculating gain rates for each angular momentum component, and obtain the critical condition for vortex nucleation. This has a similar form to previous critical conditions, but contains the angular velocity of the thermal cloud rather than of the rotating trap. We show that stirring the condensate in the absence of a thermal cloud cannot produce a vortex lattice, but it does seed angular momentum components of the condensate, which may then grow from a thermal cloud by stimulated collisions.

PHASE COHERENCE LENGTH OF AN ELONGATED BOSE-CONDENSATE VIA BRAGG SPECTROSCOPY

F. Gerbier, S. Richard, J.H. Thywissen, M. Hugbart, P. Bouyer and A. Aspect
Groupe d'Optique Atomique, Laboratoire Charles Fabryde l'Institut d'Optique,
UMRA 8501 du CNRS, Bât. 503,Campus universitaire d'Orsay,
B.P. 147, F-91403 ORSAY CEDEX, FRANCE

As shown recently both theoretically [1] and experimentally [2],the correlation properties of Bose-Einstein condensates aresignificantly affected by the trap geometry. In cigar-shaped trapswith high aspect ratio, the coherence length is predicted [1] tobe smaller than the size of the sample because of thermalfluctuations of the condensate phase. Below a characteristictemperature T_ϕ, the latter are suppressed and phasecoherence extends across the whole sample.

In our experiment, we use Doppler-sensitive Bragg spectroscopy[3] to extract the velocity distribution. We release the trapbefore probing the BEC: this reduces the density significantlyenough to avoid the mean field broadening of the line [3], s-wavecollisions between the diffracted atoms and the parent BEC [4] andsuperradiant Rayleigh scattering [5]. However, a small amount ofthe release energy [6] is converted to an axial velocity field,which produces an extremely narrow resonance (~ 100 Hz).Phase fluctuations on a length scale L_ϕ correspond to afluctuating velocity field with a width $v_\phi \sim \hbar/ML_\phi$, that broadens the resonance expected for a perfectlycoherent condensate. We will present our efforts to measurequantitatively the coherence length along the long axis of trapswith aspect ratios between 70 and 200.

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QUANTUM MONTE CARLO STUDY OF THE 3D-1D CROSSOVER FOR A TRAPPED BOSE GAS

G.E. Astrakharchik and S. Giorgini
Dipartimento di Fisica, Università di Trento, and INFM,
I-38050 Povo, Italy

We investigate the cross-over from three to one dimension in a Bose gas confined in highly anisotropic traps. By using Quantum Monte-Carlo techniques, we solve the many-body Schroedinger equation for the ground state and obtain exact results for the energy per particle and the mean square radii of the cloud in the transverse and longitudinal direction. We explicitly prove the occurrence of important beyond mean-field effects, including the appearance of Fermi-like properties as the system enters the Tonks gas regime.

VORTEX RINGS IN A CYLINDRICAL BOSE-EINSTEIN CONDENSATE

S. Komineas[1] and N. Papanicolaou[2]
[1] *Physikalisches Institut, Universitaet Bayreuth, D-95440 Bayreuth, Germany*
[2] *Department of Physics, University of Crete, and Research Center of Crete, Heraklion, Greece*

We present a calculation of solitary waves propagating in a steady state with constant velocity v along a cigar-shaped Bose-Einstein trap approximated as infinitely-elongated cylindrical. For sufficiently weak couplings (densities) the main features of the calculated solitons could be captured by effective one-dimensional (1D) models. However, for stronger couplings of practical interest, the relevant solitary waves are found to be hybrids of quasi-1D solitons and 3D vortex rings. An interesting hierarchy of vortex rings occurs as the effective coupling constant is increased through a sequence of critical values. The energy-momentum dispersion of the above structures is shown to exhibit characteristics similar to a mode proposed sometime ago by Lieb within a strictly 1D model, as well as some rotonlike features.

MACROSCOPIC PROPERTIES OF A BOSE-EINSTEIN CONDENSATE IN AN OPTICAL LATTICE

M. Krämer[1], C. Menotti[1,2], L. Pitaevskii[1,3] and S. Stringari[1]
[1]*Dipartimento di Fisica, Università di Trento, and INFM, I-38050 Povo, Italy*
[2] *Dipartimento di Matematica e Fisica, Università Cattolica del Sacro Cuore, I-25121 Brescia, Italy*
[3]*Kapitza Institute for Physical Problems, ul. Kosygina 2, 117334 Moscow, Russia*

We study the effect of a periodic optical potential on macroscopic equilibrium and dynamical properties of a Bose-Einstein condensate at zero temperature. The lattice is characterized by an interwell spacing d that is much smaller than the macroscopic size of the condensate. The barrier height V_0 is taken to be low enough to ensure the overall coherence of the system.

First we limit ourselves to the regime of relatively large barrier height V_0 where the condensate wavefunction is localized at the bottom of each well and has a small overlap with neighbouring sites (tight binding limit). Results are obtained both in presence and in absence of external harmonic trapping [1]. The modification of the equilibrium state by the lattice is accounted for by renormalizing the interaction coupling constant, while the low energy dynamics along the lattice direction is characterized by an effective mass which is directly related to the tunneling rate. The predictions for the frequencies of the collective modes are discussed for both 1D and 2D optical lattices and compared with recent experimental data [2].

Second we study the regime beyond the tight binding limit (low V_0) in absence of harmonic trapping. We obtain the sound velocity from the Bogoliubov spectrum and relate it to the effective mass and to the compressibility. Comparison with the previous results allows us to identify the regime of validity of the tight binding approximation used in [1]. Based on the equation of state we also predict the size of the condensate after expansion.

1. M. Krämer, L. Pitaevskii, and S. Stringari, *Phys. Rev. Lett.* **88**, 180404 (2002).

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DYNAMICS OF ULTRA-COLD TRAPPED DRESSED STATES

H. J. Lewandowski[1], J. M. McGuirk [1,2], D. M. Harber [1] and E. A. Cornell [1,2]
[1] *JILA, University of Colorado, Boulder, CO, USA*
[2] *Quantum Physics Division, National Institute of Standards and Technology, Boulder, Colorado, USA*

A two-level system of bosons, both above and below degeneracy, has proven to be a rich system for studying many properties, such as quantum scattering and coherence. Such a two-level system, when dressed with a resonant coupling field, can demonstrate remarkably different properties. We report the creation of a dressed two-level system of magnetically-trapped ultra-cold rubidium atoms, and we present studies of the dynamics of this system.

One of the most striking properties of the system is the creation of a Bose-Einstein condensate from a coherent superposition of the two dressed states. This dressed condensate forms into a state which oscillates between the bare states. Additionally we observe complicated dynamics in the system including spatial separation of dressed condensates and spin waves in dressed normal clouds. The behavior of the system may be altered by varying the dressed state energy-splitting relative to the thermal energy of the atoms.

SPIN-DISORDERED SUPERFLUID STATE FOR SPIN-1 BOSONS WITH FRACTIONAL SPIN AND STATISTICS

W. Vincent Liu[1,2] and Xiao-Gang Wen[2]
[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2] *Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

We study a strongly correlated spin-1 Bose gas in 2D space by using the projective construction. A spin-disordered superfluid state is constructed. In this state, spin-1 bosons form clusters of various size such as clusters of 2 bosons (dimer), 3 bosons (triangle), 4 bosons, etc. Each cluster is a spin singlet and is totally symmetric among all bosons within the cluster. Quantitatively, an l-cluster is described by $C_l(\{\mathbf{r}_i, m_i\}_{i=1\ldots l}) = \prod_{i=1}^{l} g(\mathbf{r}_i - \mathbf{r}_{i+1}) \{\prod_{i=1}^{l} \epsilon\, \mathcal{C}^{m_i}\}$ (with $\mathbf{r}_{l+1} \equiv \mathbf{r}_1$ identified), where $g(\mathbf{r})$ is a pairing wavefunction of p_{x+iy}-symmetry (thus *odd* in $\mathbf{r}$), ϵ is a 2×2 antisymmetric matrix, and $\mathcal{C}^m$ is a (symmetric) 2×2 matrix defined by the Clebsch-Gordan coefficients for $\frac{1}{2}\otimes\frac{1}{2}$, $\mathcal{C}^m_{\alpha\beta} \equiv \langle (SS_z)1m|\frac{1}{2}\frac{1}{2};\alpha\beta\rangle$. The state is a superposition of all possible cluster configurations, each having a specific weight factor.

We found at mean field level that the above state minimizes the interaction energy substantially better than the conventional polar condensate if the interaction is antiferromagnetic. This novel state has, besides a conventional superfluid mode, a non-trivial topological order whose low energy excitations carry fractional spin, charge, and statistics. The spin excitations become gapless only at the edge and are described by level-1 SU(2) Kac-Moody algebra. The edge state is identical to the edge state of the chiral spin liquid or the right moving sector of spin-1/2 chain.

1. W. V. Liu and X.-G. Wen, cond-mat/0201187.

INTERIOR GAP SUPERFLUIDITY

W. Vincent Liu and Frank Wilczek
Center for Theoretical Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139-4307, USA

Recent developments in ultracold alkali atomic gases have revitalized interest in some basic qualitative questions of quantum many-body theory, because they promise to make a wide variety of conceptually interesting parameter regimes, which might previously have seemed academic or excessively special, experimentally accessible. With this motivation, and stimulated by questions in quantum chromodynamics (QCD) at high density, we here revisit the question of fermion pairing between species whose Fermi surfaces do not precisely match. We propose a new state of matter in which the pairing interactions carve out a gap within the interior of a large Fermi ball, while the exterior surface remains gapless. This defines a system which contains both a superfluid and a normal Fermi liquid simultaneously, with both gapped and gapless quasiparticle excitations. This state can be realized at weak coupling. We predict that a cold mixture of two species of fermionic atoms with different mass will exhibit this state. A possible experiment setup to verify our prediction can be, for instance, a cold mixture of (fermionic) ^{6}Li and ^{40}K atoms. The transition temperature in such a system is estimated to be of the same order as one would expect of BCS superfluidity in cold atoms of equal mass. We see no reason why interior gap superfluidity could not be realized, in appropriate solids, for electrons. In that case, it would define a material that is simultaneously superconducting and metallic.

NANODEPOSITION OF COLD GALLIUM ATOMS

O.M.Maragò[1,2], B.Fazio[1], P.G.Gucciardi[1],
F.Fuso[2],C.Vasi[1], and E.Arimondo[2].
[1] *CNR-Istituto per i Processi Chimico-Fisici, sez. Messina*
Via La Farina 237, I-98123 Messina, Italy
[2] *INFM,Unit Pisa, Via Buonarroti 2, I-56127, Pisa, Italy*

Nanofabrication with Atom Lithography has become a subject of investigation in recent years [1]. This new technique is based on two steps: first the use of laser cooling methods for the high collimation of the atomic beam, secondly the focusing of atoms through a laser beam in standing wave configuration. This process produces an ordered pattern with a precise spacing determined by the laser wavelength. The main goal of our work is to demonstrate, for the first time, the Atom Lithography of Gallium atoms [2,3]. This will open the way for the integration of Atom Lithography with standard deposition methods, with the ultimate goal of industrial-scale fabrication of regularly ordered nanosized structures. This experiment is part of the NANOCOLD EC RTD project IST-32264-2001 [4].

1. J. McClelland, *Nanofabrication via Atom Optics*, *Handbook of Nanostructured Materials and Nanotechnology*, Academic press.

2. Preliminary results on 1D laser conditioning of Gallium have been obtained by the group of S.A. Lee at Colorado State University (USA), http:/ / www.physics.colostate.edu/ groups/ lasers/ .

3. Work is in progress at Uni-Bonn to demostrate laser cooling and nanodeposition of Indium, http:/ / www.iap.uni-bonn.de/ arb_m_e.html.

4. NANOCOLD web page: http:/ / nanocold.df.unipi.it/ .

SPIN WAVES IN AN ULTRA-COLD GAS

J. M. McGuirk [1,2], H. J. Lewandowski[2], D. M. Harber [2] and E. A. Cornell [1,2]
[1] *Quantum Physics Division, National Institute of Standards and Technology, Boulder, Colorado, USA*
[2] *JILA, University of Colorado, Boulder, CO, USA*

We report the observation of spin waves in an ultra-cold magnetically-trapped gas [1]. Spin waves are macroscopic collective excitations which arise from the need to symmetrize the scattered wavefunction when indistinguishable particles interact. When two atoms collide, this exchange scattering contribution results in interference between the forward and backward scattered waves, which in turn leads to a velocity-dependent rotation of the spins of the colliding atoms. After many such scattering events, inhomogeneities in the spin field propagate in a macroscopic spin current. Out of equilibrium spin configurations lead to oscillations in the spin field of the trapped gas known as spin waves.

Using high precision Ramsey spectroscopy and spin-state selective absorption imaging, we probe the spin configuration of a cloud of rubidium atoms above the Bose-Einstein condensation transition temperature initially prepared in an equal superposition of two hyperfine groundstates. A quadrupole spin wave mode is excited using the curvature of the trapping potential. We extract both the longitudinal and transverse components of the Bloch vector as functions of time and spatial position along the axis of the cloud. The effects of cloud density, temperature and spin-state energy splitting inhomogeneity on the wavelength, frequency, and damping time of the spin waves are presented. Additionally, the complete trajectories of the Bloch vector on the Bloch sphere are determined for each position in the cloud. The equilibrium spin configuration is studied as a function of the inhomogeneity of the frequency splitting between the two spin states.

1. J. M. McGuirk, H. J. Lewandowski, D. M. Harber, T. Nikuni, J. E. Williams, E. A. Cornell, cond-mat/0204182.

EXPANSION OF AN INTERACTING FERMI GAS

C. Menotti[1,2] , P. Pedri[1] and S. Stringari[1]
[1] *Dipartimento di Fisica, Università di Trento, and INFM, I-38050 Povo, Italy*
[2] *Dipartimento di Matematica e Fisica, Università Cattolica del Sacro Cuore, I-25121 Brescia, Italy*

We study the expansion of an ultracold sample of fermions initially trapped in a anisotropic harmonic trap. We show that, similarly to the case of a Bose-Einstein condensed gas, the expansion of the cloud provides valuable information about the state of the system and the role of interactions. In particular the time evolution of the deformation of the expanding cloud behaves quite differently depending on whether the system is in the normal or in the superfluid phase. For the superfluid phase we predict an inversion of the deformation of the sample, similar to what happens with Bose-Einstein condensates. Viceversa, in the normal phase the inversion of the aspect ratio is never achieved, unless the mean field interaction is repulsive.

The description of the expansion of a fermionic gas in the normal and superfluid phase requires different theoretical approaches. For the normal phase at low temperature, we use the formalism of the Vlasov equations, while in the superfluid phase we study the expansion by means of the hydrodynamic theory of superfluids. Even using the same equation of state for the normal and superfluid phases, the results of the expansion are different since the equations governing the dynamics are different in the two cases.

FERMI-BOSE AND BOSE-BOSE QUANTUM DEGENERATE MIXTURES

G. Roati, F. Riboli, M. Modugno, G. Modugno, and M. Inguscio
LENS and Dipartimento di Fisica, Universitá di Firenze, and INFM

We present the experimental investigation on binary atomic mixtures composed by ^{87}Rb and isotopes of potassium. The atomic samples are simultaneously trapped and cooled in a double magneto-optical apparatus and then transfered in a magnetic trap, where potassium atoms are sympathetically cooled by means of thermal exchange with evaporatively cooled rubidium atoms [1]. The interspecies interaction properties of the pairs ^{40}K - ^{87}Rb and ^{41}K - ^{87}Rb are favorable for the formation of Fermi-Bose and Bose-Bose quantum degenerate gases, respectively [2].

We indeed produce ^{87}Rb Bose-Einstein condensates immersed in a Fermi sea of ^{40}K atoms, at a temperature $T \leq 0.3T_F$ [3]. The peculiar attractive interaction of this mixture is promising for the study of sympathetic cooling deep into the degenerate regime.

We also produce binary Bose-Einstein condensates of ^{41}K and ^{87}Rb atoms, and we evidence their superluid behavior in the dynamics in the magnetic trap. The large repulsive interaction makes this system interesting for the study of immiscible superfluids.

1. G. Modugno, G. Ferrari, G. Roati, A. Simoni, and M. Inguscio, *Science* **294**, 1320 (2001).

2. G. Ferrari, M. Inguscio, W. Jastrzebski, G. Modugno, G. Roati, and A. Simoni, cond-mat/0202290.

3. G. Roati, F. Riboli, G. Modugno, and M. Inguscio, cond-mat/0205015.

1D MODEL FOR THE DYNAMICS AND EXPANSION OF ELONGATED BOSE-EINSTEIN CONDENSATES

Pietro Massignan[1] and Michele Modugno[1]
[1] *LENS and Dipartimento di Fisica, Università di Firenze*
Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy

We present a 1D effective model for the evolution of a cigar-shaped Bose-Einstein condensate in time dependent potentials whose radial component is harmonic. We apply this model to investigate the dynamics and expansion of condensates in 1D optical lattices, by comparing our predictions with recent experimental data and theoretical results. This model might be useful to analyze future experiments in 1D optical lattices.

ROTATING BOSE CLUSTERS

Erich Müller and Tin-Lun Ho
Dept. of Physics, The Ohio State University, Columbus OH 43210

This poster illustrates some of the remarkable quantum hall and spin liquid properties of small clusters of rotating bosons, and suggests methods for creating and measuring these highly unusual states.

We propose loading atoms into an optical lattice to create an array of small clusters, each with of order 100 atoms. Each cluster can be rotated by applying a rotating quadrupolar field. As the clusters are spun-up, more and more vortices enter each cluster – forming a regular lattice. When the number of vortices is comparable to the number of particles the vortex lattice melts due to quantum fluctuations and the system goes through a series of states analogous to those found in quantum-hall systems. These states can be probed by simply turning off the lasers which generate the optical lattice. In the fast rotating limit, we have shown that each cluster will expand with a simple scaling form. The clusters overlap, and an absorption image will give ensemble averaged information about the clusters. The quantum-hall nature of the states will be revealed by a very flat density profile.

The situation is even more interesting in the case of spin-1 bosons, especially those with antiferromagnetic interactions. In the absence of rotation such clusters possess a fragmented condensate. As the system is spun-up, the condensate fragments into even more pieces and the spins develop non-trivial correlations, referred to as a spin-liquid structure. At high rotation speeds the bosonic quantum state factors into a product of two fermionic wavefunctions, one of which encodes the spin correlations, and the other is a Slater determinant which can be viewed as attaching flux lines to the bosons and creating fermionic composite particles.

1. Tin-Lun Ho and Erich Mueller *Phys. Rev. Lett.* in press (2002). preprint: cond-mat/0203143

THERMODYNAMICS OF A BRIGHT BOSONIC SOLITON

Vanja Dunjko[1], Christopher P. Herzog[2,3], Yvan Castin[3], Maxim Olshanii[1,3,4]
[1]*Department of Physics & Astronomy, University of Southern California, Los Angeles, CA 90089-0484, USA*
[2]*Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[3]*Ecole Normale Supérieure, Laboratoire Kastler-Brossel, 24 Rue Lhomond, 75231 Paris Cedex 05, France*
[4]*Institute for Theoretical Atomic and Molecular Physics, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

Following the recent successful experimental observation of a bosonic soliton (Kevin E. Strecker *et al*, ⟨cond-mat/0204532⟩; L. Khaykovich *et al*, Science, **296**, 1290 (2002)) we develop a semi-phenomenological theory for the soliton thermodynamics, predicting in particular the condensation temperature. We suggest a modified thermodynamic limit where the condensate formation resembles a first order phase transition, leading to a discontinuity in the dependence of the condensate occupation on temperature.

BREAKDOWN OF SUPERFLUIDITY OF AN ATOM LASER PAST AN OBSTACLE

Nicolas Pavloff
Laboratoire de Physique Théorique et Modèles Statistiques
Université Paris Sud, bât. 100, F-91405 Orsay Cedex, France
email: pavloff@ipno.in2p3.fr

The 1D flow of a continuous beam of Bose-Einstein condensed atoms in presence of an obstacle is studied as a function of the beam velocity and of the type of perturbing potential (representing the interaction of the obstacle with the atoms of the beam). We identify the relevant regimes: stationary/time-dependent and superfluid/dissipative; the absence of drag being used as a criterion for superfluidity.

There exists a critical velocity below which the flow is superfluid. For attractive obstacles, we show that this critical velocity can reach the value predicted by Landau's approach. Besides, for penetrable obstacles, it is shown that superfluidity is recovered at large beam velocity.

The drag is computed in the non-superfluid regime. We study in detail specific model potential (attractive 'and/or repulsive) representing the obstacle (a weak potential, a delta peak, a square well and a Gaussian potential). For non-stationary flows, this is done by numerical integration of the 1D reduction of the Gross-Pitaevksii equation. For stationary flows (i.e., at large velocity) a simple method allows in most of the cases an analytical determination of the drag.

An interesting outcome of this computation is to show that, due to non-linearities, enormous differences in drag (and in energy transfer rate to the condensate) can occur when switching from repulsive to attractive potentials (provided the potential is strong enough).

1. P. Leboeuf and N. Pavloff, Phys. Rev. A **64**, 033602 (2001).

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CONSEQUENCE OF SUPERFLUIDITY ON THE EXPANSION OF A ROTATING BOSE-EINSTEIN CONDENSATE

M. Edwards[1,2], Charles W. Clark [2], P. Pedri[3], L. Pitaevskii [3,4] and S. Stringari[3]
[1] *Department of Physics, Georgia Southern University, Statesboro, Georgia, USA*
[2] *National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8410* [3] *Dipartimento di Fisica, Università di Trento, and INFM, I-38050 Povo, Italy*
[4] *Kapitza Institute for Physical Problems, ulitza Kosygina 2, 117334 Moscow, Russia*

We propose an easily detectable signature of superfluidity in rotating, vortex-free gaseous Bose-Einstein condensates. We have studied the time evolution of the expansion of such a condensate after it is released from the confining trap. We find that if such a condensate is not initially rotating, then at some moment it will instantaneously achieve a circular cross section. If the condensate is initially rotating its irrotational flow and the conservation of angular momentum prevent the released condensate from attaining a circular cross section, since the instantaneous moment of inertia is then proportional to the asymmetry of this cross section.

EXPANSION OF A BOSE-EINSTEIN CONDENSATE IN AN ATOMIC WAVEGUIDE

L. Plaja[1] and L. Santos[2]
[1] *Departamento de Física Aplicada, Universidad de Salamanca, E-37008 Salamanca, Spain*
[2] *Institut für Theoretische Physik, Universität Hannover, D-30167 Hannover,Germany*

The expansion of a Bose–Einstein condensate in an atomic waveguide is analyzed. We study different regimes of expansion, and identify a transient regime between one–dimensional and three–dimensional dynamics, in which the properties of the condensate and its further expansion can be well explained by reducing the transversal dynamics to a two–level system. The relevance of this regime in current experiments is discussed.

1. L. Plaja and L. Santos, *Phys. Rev. A* **65**, 035602 (2002).

STRUCTURE AND STABILITY OF DEGENERATE BOSON-FERMION MIXTURES

Robert Roth and Keith Burnett
Clarendon Laboratory, University of Oxford, Parks Road,
Oxford OX1 3PU, United Kingdom

Within the past year a whole family of experiments on the production of degenerate mixtures of bosonic and fermionic atoms proved successful. Currently four different types of degenerate mixtures are available: Mixtures of ^{7}Li and ^{6}Li with two different combinations of hyperfine states [1,2], a mixture of ^{23}Na and ^{6}Li [3], and a mixture of ^{87}Rb and ^{40}K [4]. Due to the different interaction parameters they all show completely different ground state properties.

In this contribution the zero-temperature phase diagram of binary boson-fermion mixtures is discussed as function of the boson-boson and the boson-fermion s-wave scattering lengths. The bosonic component is described using a Gross-Pitaevskii equation which is coupled self-consistently to the fermionic component. The fermion density is described within the Thomas-Fermi approximation [5,6].

For different combinations of repulsive and attractive boson-boson and boson-fermion interactions different types of density profiles and mean-field instabilities can be observed [5,6]. For attractive boson-boson interactions (like for one of the ^{7}Li-^{6}Li mixtures [1,2]) the isolated mean-field collapse of the bosonic component dominates the properties of the system; the boson-fermion interaction modifies the stability limit only marginally. A different kind of mean-field collapse is induced by attractive boson-fermion interactions (present in the ^{87}Rb-^{40}K mixture [4]). Here both species show an enhancement of the density within the overlap region; sufficiently strong boson-fermion attractions can cause a simultaneous collapse of both species. Repulsive boson-fermion interactions, on the other hand, reduce the overlap between the two species and lead to the spatial separation of the components.

The characteristic changes of the density profiles as function of the scattering lengths and critical particle numbers for all of these transitions are discussed in detail. Finally, the specific properties and prospects of the boson-fermion mixtures available in present experiments are addressed [6].

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4 G. Roati, et al., **cond-mat/0205015** (2002).

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DYNAMICAL PROPERTIES OF BOSE-CONDENSED BRIGHT SOLITONS UNDER TRANSVERSE CONFINEMENT

Luca Salasnich[1], A. Parola[2], and L. Reatto[1]
[1] *Istituto Nazionale per la Fisica della Materia, Unità di Milano, Dipartimento di Fisica, Università di Milano, Via Celoria 16, 20133 Milano, Italy*
[2] *Istituto Nazionale per la Fisica della Materia, Unità di Como, Dipartimento di Scienze Fisiche, Università dell'Insubria, Via Valleggio 11, 23100 Como, Italy*

We investigate the dynamics of Bose-condensed bright solitons made of alkali-metal atoms with negative scattering length and under harmonic confinement in the transverse direction [1]. By comparing the results of the 3D Gross-Pitaevskii equation (3D GPE) with those of the 1D GPE, we find a good agreement only for weakly-interacting bright solitons. In particular, contrary to the 1D case [2], the 3D bright soliton does not exist anymore above a critical attractive interaction. Analyzing the macroscopic quantum tunneling of the bright soliton on a Gaussian barrier we find that its interference in the tunneling region is strongly suppressed with respect to the non-solitonic case. We show that the collapse of the soliton is induced by the scattering on the barrier or by the collision with another matter wave when the density reaches a critical value, for which we derive an accurate analytical formula. Finally, by using an effective 1D nonpolynomial nonlinear Schrödinger equation (NPSE), which accurately takes into account the transverse dynamics of cigar-like condensates, we numerically simulate the dynamics of the "soliton train" reported in a recent experiment [3].

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CHARACTERIZATION OF A 2D-MOT AS A SOURCE OF COLD ATOMS

Holger Schmaljohann[1], Michael Erhard[1], Markus Kottke[2], Jochen Kronjäger[1], Sebastian van Staa[1] ,and Klaus Sengstock[1]
[1] *Institut fr Laserphysik, Universität Hamburg, Jungiusstraße 9, 20355 Hamburg, Germany*
[2] *Institut fr Quantenoptik, Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*

We are planing and building a new experiment on Bose-Einstein Condensation with Rubidium atoms. Here we report on the status of the experiment. The compact experiment consists of a double MOT system operated with semiconductor lasers. We give a characterization of the two dimensional MOT as a source of slow atoms. We also show our design of the magnetic trap and the first measurements on lifetime and evaporation.

1. K. Dieckmann *et al.*, *PRA* **58**, 3891 (1998).
2. J. Schoser *et al.*, *physics/0201034* (2002).
3. L.V. Hau *et al.*, *PRA* **58**, R54 (1998).

RENORMALIZED KINETIC THEORY OF BOSE-EINSTEIN CONDENSATION

Jochen Wachter[1], Reinhold Walser[2], and Murray Holland[1]
[1] *JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA*
[2] *Universität Ulm, Abteilung für Quantenphysik, D-89069 Ulm, Germany*

We present a kinetic theory, which includes binary interactions to second order and is formulated in terms of a quantum Boltzmann equation for Bogoliubov quasiparticles. The first-order interactions are expressed as many-body T matrices and thus include the correct renormalized scattering physics. This renormalized theory is gapless by construction. Thus, the excited Bogoliubov modes are naturally orthogonal to the condensate ground state. We have numerically simulated the quasiparticle Boltzmann equation for a simple, spherically symmetric system and obtained the linear-response eigenfrequencies and damping rates.

COLLECTIVE SPIN DYNAMICS IN A TRAPPED BOSE GAS

J. E. Williams[1], T. Nikuni[2], and C. W. Clark[1]
[1] *NIST, Gaithersburg, Maryland, USA*
[2] *Tokyo University of Science, Tokyo, Japan*

An ultra-cold Bose gas of two-level atoms can be thought of as a spin-1/2 Bose gas. It supports spin-wave collective modes due to the exchange mean field. Such collective spin oscillations have been observed in recent experiments at JILA with ^{87}Rb atoms confined in a harmonic trap [1]. We present a theory of the spin-wave collective modes based on the moment method for trapped gases [2]. In the collisionless and hydrodynamic limits, we derive analytic expressions for the frequencies and damping rates of modes with dipole and quadrupole symmetry. We find that the frequency for a given mode is given by a temperature independent function of the peak density n, and falls off as $1/n$. We also find that, to a very good approximation, excitations in the radial and axial directions are decoupled. We compare our model to the numerical integration of a one-dimensional version of the kinetic equation and find very good qualitative agreement. The damping rates, however, show the largest deviation for intermediate densities, where one expects Landau damping—which is unaccounted for in our moment approach—to play a significant role.

1. J. M. McGuirk, H. J. Lewandowski, D. M. Harber, T. Nikuni, J. E. Williams, and E. A. Cornell, cond-mat/0204182.

2. T. Nikuni, J. E. Williams, and C. W. Clark, cond-mat/0205450.

RESONANT BOSE CONDENSATE: ANALOG of a RESONANT ATOM

V.I. Yukalov[1], E.P. Yukalova[2]
[1] *Bogolubov Laboratory of Theoretical Physics*
Joint Institute for Nuclear Research, Dubna 141980, Russia
[2] *Department of Computational Physics, Laboratory of Information Technologies*
Joint Institute for Nuclear Research, Dubna 141980, Russia

The possibility of resonant formation of nonlinear coherent modes in trapped Bose-Einstein condensates has been recently advanced [1]. These modes represent nonground-state Bose condensates. We have developed a complete theory of the resonant excitation of the nonlinear coherent modes. The latter can be created by modulating the trapping potential with a frequency tuned close to the transition frequency between the two chosen modes. The requirement that the transition amplitudes be smaller than the transition frequency imposes a constraint on the number of particles that can be transferred to an excited mode. The stability analysis is presented and illustrated by the corresponding phase portraits. The origin of dynamic critical phenomena, discovered numerically [2–4], is elucidated. It is shown that these critical phenomena occur when the saddle separatrix is crossed by the starting point of a trajectory. Interference patterns and interference current are investigated and are shown to oscillate on two time scales, slow and fast. Atomic spin squeezing and multiparticle entanglement are studied. The developed theory suggests a generalization of resonant effects in optics to nonlinear systems of Bose-condensed atoms.

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ENTANGLED ATOMIC GAS AND A MOLECULAR BOSE-EINSTEIN CONDENSATE FORMED BY FESHBACH RESONANCE

Vladimir A. Yurovsky and Abraham Ben-Reuven
School of Chemistry, Tel Aviv University, 69978 Tel Aviv, Israel

Processes of association in an atomic Bose-Einstein condensate, and dissociation of the resulting molecular condensate, due to Feshbach resonance in a time-dependent magnetic field, are analyzed incorporating non-mean-field quantum corrections and inelastic collisions. Calculations for the Na atomic condensate demonstrate that there exist optimal conditions under which about 80atomic population can be converted to a relatively long-lived molecular condensate (with lifetimes of 10 ms and more). Under different conditions, entangled atoms in two-mode squeezed states (with noise reduction of about 30 dB) may also be formed by molecular dissociation. A gas of atoms in squeezed or entangled states can have applications in quantum computing, communications, and measurements.

Chapter 3

PARTICIPANTS

Ennio Arimondo	arimondo@mail.df.unipi.it
Jan Arlt	arlt@iqo.uni-hannover.de
Alain Aspect	alain.aspect@iota.u-psud.fr
Grigori Astrakhartchik	astra@science.unitn.it
Gordon Baym	baym@rsm1.physics.uiuc.edu
Mikhail Baranov	baranov@itp.uni-hannover.de
Andrea Bertoldi	abertold@science.unitn.it
Jean-Paul Blaizot	blaizot@spht.saclay.cea.fr
Thomas Bourdel	bourdel@clipper.ens.fr
Philippe Bouyer	philippe.bouyer@iota.u-psud.fr
Christoph Bruder	christoph.bruder@unibas.ch
Keith Burnett	k.burnett1@physics.ox.ac.uk
Tommaso Calarco	calarco@ect.it
Francesco Cataliotti	fsc@lens.unifi.it
Ananth Chikkatur	ananth@MIT.EDU
Maria Luisa Chiofalo	marilu@ducky.sns.it
Charles Clark	charles.clark@nist.gov
Roland Combescot	Roland.Combescot@lps.ens.fr
Eric Cornell	ecornell@jilau1.Colorado.EDU
Marco Cozzini	cozzini@science.unitn.it
Franco Dalfovo	dalfovo@science.unitn.it
Jean Dalibard	Jean.Dalibard@lkb.ens.fr
Diego A. R. Dalvit	dalvit@lanl.gov
Nir Davidson	nir.davidson@weizmann.ac.il
Mark Edwards	edwards@amo.phy.gasou.edu
Tilman Essinger	tilman.esslinger@iqe.phys.ethz.ch
Giovanni Falco	G.M.Falco@phys.uu.nl
Alexander Fetter	fetter@stanford.edu
Chiara Fort	fort@lens.unifi.it
Jean-Noël Fuchs	jean-noel.fuchs@lkb.ens.fr
Dimitri M. Gangardt	Dimitri.Gangardt@lkb.ens.fr

Juan Jose Garcia-Ripoll	jlr@mpq.mpg.de
Crispin Gardiner	crispin.gardiner@vuw.ac.nz
Fabrice Gerbier	fabrice.gerbier@iota.u-psud.fr
Stefano Giorgini	giorgini@science.unitn.it
Markus Greiner	markus.greiner@physik.uni-muenchen.de
Allan Griffin	griffin@physics.utoronto.ca
Muntsa Guilleumas	muntsa@ecm.ub.es
Albrecht Haase	haase@physi.uni-heidelberg.de
Jason Ho	HO@mps.ohio-state.edu
Eleanor Hodby	e.hodby1@physics.ox.ac.uk
Murray Holland	murray.holland@colorado.edu
Randy Hulet	randy@atomcool.rice.edu
Stavros Komineas	Stavros.Komineas@uni-bayreuth.de
Meret Kraemer	kraemer@science.unitn.it
Fabrizio Illuminati	illuminati@sa.infn.it
Massimo Inguscio	inguscio@lens.unifi.it
Wolfgang Ketterle	ketterle@MIT.EDU
Franck Laloe	laloe@ens.fr
Igor Lesanovsky	Lesanovsky@t-online.de
Leonid Levitov	levitov@MIT.EDU
Heather Lewandowski	lewandoh@colorado.edu
W. Vincent Liu	wvliu@mit.edu
Pasquale Maddaloni	maddaloni@lens.unifi.it
Onofrio Maragò	marago@its.me.cnr.it
Jeffrey McGuirk	mcguirk@jilau1.colorado.edu
Chiara Menotti	chiara@science.unitn.it
Michele Modugno	modugno@fi.infn.it
Giovanni Modugno	modugno@lens.unifi.it
Klaus Mølmer	moelmer@ifa.au.dk
Oliver Morsch	morsch@df.unipi.it
Ben Mottelson	mottelson@nordita.dk
Erich Müller	emueller@mps.ohio-state.edu
Maxim Olshanii	olshanii@physics.usc.edu
Nicolas Pavloff	pavloff@ipno.in2p3.fr
Paolo Pedri	pedri@science.unitn.it
Chris Pethick	pethick@nordita.dk
Dmitry Petrov	petrov@amolf.nl
Lev Pitaevskii	lev@science.unitn.it
Luis Plaja	lplaja@usal.es
Alessio Recati	recati@science.unitn.it
Leonardo Ricci	ricci@science.unitn.it
Steven Rolston	steven.rolston@nist.gov
Robert Roth	r.roth@gsi.de
Kazik Rzazewski	kazik@cft.edu.pl
Luca Salasnich	salasnich@mi.infm.it

Christophe Salomon	christophe.salomon@lkb.ens.fr
Luis Santos	santos@itp.uni-hannover.de
Holger Schmaljohann	holger.schmaljohann@physnet.uni-hamburg.de
Robert Seiringer	rseiring@Math.Princeton.EDU
Klaus Sengstock	klaus.sengstock@physnet.uni-hamburg.de
Gora Shlyapnikov	shlyapnikov@amolf.nl
Augusto Smerzi	smerzi@cnls.lanl.gov
Sandro Stringari	stringar@science.unitn.it
Henk T.C. Stoof	stoof@phys.uu.nl
Cesare Tozzo	c.tozzo@dmf.unicatt.it
Slava Yukalov	yukalov@thsun1.jinr.ru
Vladimir Yurovsky	volodia@post.tau.ac.il
Luciano Viverit	luciano.viverit@mi.infn.it
Jochen Wachter	Wachter@colorado.edu
Jamie Williams	jamiew@nist.gov
Eugene Zaremba	zaremba@sparky.phy.queensu.ca
Peter Zoller	Peter.Zoller@uibk.ac.at

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