Obergurgl Meeting 2003

Quantum Optics Innsbruck

February 23 – March 01

Daily Program

Monday 24

Breakfast: 7:30 a.m.

Conference Room

I. Bloch 8:30 - 9:05
Controlled Collisions with Neutral Atoms in Optical Lattices

M. Lewenstein 9:05 - 9:40
Quantum correlations in systems of identical particles: from quantum gates to quantum phase transitions

J. von Delft 9:40 - 10:05
DMRG-study of ultracold bosonic atoms in an optical lattice

A. Hines 10:05 - 10:30
Entanglement of two-mode Bose-Einstein condensates

Brunch / SPORTS: 10:30 - 16:00

F. Schmidt-Kaler 16:00 - 16:35
Single Ions for Quantum Information Processing

P. Grangier 16:35 - 17:10
Manipulating individual atoms for quantum information processing

W. Schleich 17:10 - 17:35

A. Zeilinger 17:35 - 18:00
Recent Progress in Quantum Teleportation with Photonic Qubits

Dinner: 18:00 - 19:30

POSTER: 19:30 - 21:00

Controlled Collisions with Neutral Atoms in Optical Lattices

Markus Greiner, Olaf Mandel, Artur Widera, Tim Rom,
Theodor W. Hänsch & Immanuel Bloch

Ludwig-Maximilians-Universität München, Sektion Physik, München &
Max-Planck Institut für Quantenoptik, Garching

When neutral atoms from an atomic Bose-Einstein condensate are loaded into a three dimensional optical lattice potential, one can observe a transition to a Mott insulating regime, where each lattice site is ideally occupied by a single atom. Such a Mott insulator provides a unique environment for quantum information processing, where a qubit is formed by a single atom on a lattice site and a large number of lattice sites of up to 10^5 can be filled with atoms. So far mainly state independent optical lattice potentials have been used to trap Bose-Einstein condensates. However it has been realized that by using spin-dependent potentials one could bring atoms on neighboring lattice sites into contact and thereby realize fundamental quantum gates, excite spin waves, study quantum random walks or realize an almost universal quantum simulator that could be used to study fundamental condenses matter physics Hamiltonians, which are difficult to solve on classical computers. We present our latest results on such controlled collisions between neutral atoms in optical lattices by using spin-dependent optical potentials. In the talk, different signatures of the coherent collisional dynamics of atoms on neighboring lattice sites will be discussed, as well as the possibility to realize a tuneable interstate interaction between atoms on a single lattice site.

Quantum correlations in systems of identical particles: from quantum gates to quantum phase transitions

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We analyze a general question of characterization and classification of quantum correlations in systems of identical particles. We are specially interested in characterising quantum correlations that are *useful*, i.e. can be used for various applications in quantum information, quantum communication, or precision metrology. We consider two generic types of situations. The first situation, which concerns for instance quantum gates [1], is such in which the multipartite system consists of well separated parties that are brought together to interact at distances at which quantum statistics is relevant. The second situation concerns large quantum statistical systems, in which all particles feel their quantum statistics in interactions, but remote parts of the system may be regarded as separated parties.

We pose the question what kind of quantum correlations have to be generated during the interaction in order to generate entanglement, or specific kind of entanglement in the separated parties. We discuss various mathematical and physical ways of formulating this question and report results concerning classification and characterization of quantum correlations using the concept of Slater number [2,3].

We illustrate this problem by modelling quantum gates based on motional states [4] and delocalized qubits [5] in arrays of optical traps. We study also quantum correlations of bosonic atoms in optical lattices and photons in various media. Finally, we will also mention the possibilities of engineering Schrödinger cat states and entangling strings of atoms in 1D pipelines [6].

03.67.Dd, 03.67.Hk, 03.67.-a

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DMRG-study of ultracold bosonic atoms in an optical lattice

Recently, a phase transition between a superfluid and a Mott-insulating phase has been realized experimentally [1] in a system of ultracold bosonic atoms in an optical lattice. Theoretically, this can in some parameter regimes be modeled by a Bose-Hubbard Hamiltonian (see [2]). We have investigated the properties of the Mott-insulator and the superfluid phase in an one dimensional system described by the Bose-Hubbard Hamiltonian with the help of the Density-Matrix-Renormalization group method (DMRG). The DMRG is a numerical method which was developed in the area of condensed matter theory to investigate static and dynamic properties of strongly correlated quasi-one-dimensional quantum systems. We present results for the density distribution in momentum space (for systems of about 128 sites) a quantity which can be related to the interference pattern measured by the time-of flight analysis in the experiment of Greiner et al [1]. We find that the height of the central interference maximum obeys approximately a scaling relation as a function of the system size.

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Entanglement of two-mode Bose-Einstein condensates

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I will discuss the entanglement characteristics of two general bimodal Bose-Einstein condensates - a pair of tunnel-coupled Bose-Einstein condensates and the atom-molecule Bose-Einstein condensate. We argue that the entanglement is only physically meaningful if the system is viewed as a bipartite system, where the subsystems are the two modes. The indistinguishibility of the particles in the condensate means that the atomic constituents are physically inaccessible and thus the degree of entanglement between individual particles, unlike the entanglement between the modes, is not experimentally relevant so long as the particles remain in the condensed state. We considered the entanglement between the two modes for the exact ground state of the two bimodal condensates and consider the dynamics of the entanglement in the tunnel-coupled case.

Single Ions for Quantum Information Processing

We are interested in **Quantum Information Processing** (QI) using a string of trapped ions, where each ion represents a bit quantum information (qubit). The experimentally most challenging operation towards this goal is to implement quantum logic gate operations on this quantum register. We present the realization of **single and two-qubit gates** (Cirac&Zoller gate proposal, 1995).

As a first proof of principle, and to show the feasibility of QI, we have implemented the **Deutsch algorithm** (Deutsch&Jozsa, 1992) : The answer to the question wheter a coin is fair (head on one side, tails on the other) or fake (both sides equal) requires two examinations, i.e. a look on both sides for any classical algorithm. However, if the problem is represented by operations of a quantum processor, only one examination is necessary to answer this question.

Finally, we outline a method to convert static qubits (e.g. as stored in a string of ions) into photonic ("flying") qubits. Merging techniques from **cavity-QED and ion trapping**, we are able to localize an ion within a few nm in the waist of a high finesse cavity mode and observe coherent dynamics between cavity field and ion tow-level system. Further, we report the observation of the Purcell effect, a reduction of life time of the atoms's state, if the cavity is resonant with the atomic transition.

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Manipulating individual atoms for quantum information processing.

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Abstract: We will describe several experiments where single atoms are used towards applications in quantum information processing and communications. One experiment is based upon a very small optical dipole trap, designed to store and manipulate individual atoms, and the perspectives for using this system for quantum information processing will be discussed. The other experiment uses individual nitrogen atoms, embedded in a diamond nanocrystal, in order to emit single photons "on demand". This single photon source has been used to implement a full quantum key distribution protocol using "true" single photons.

There is currently a strong interest for the manipulation of individual neutral atoms in various settings. Besides their fundamental interest, the manipulations of individual quantum objects may open the way to controlled engineering of the quantum state of small sets of trapped particles, in order to encode and process information at the quantum level.

In this context, we have demonstrated that it is possible to load and detect individual atoms in an optical dipole trap with a sub-micrometer size [1-2]. The experimental set-up consists of a strongly focused dipole trap, produced by an objective that gives a diffraction-limited spot of 0.7 µm. It has been observed that the trap can contain only one (or zero) atom over a wide range of loading rates. This behaviour is well reproduced by a simple "collisional blockade" model, that includes loading, one-body decay, and two-body decay [2]. In the collisional blockade regime, two-body decay is the dominant loss mechanism as soon as there are two atoms in the trap.

Once one single atom is loaded in the trap, one can measure its temperature and oscillation frequencies. From our measurements the typical oscillations frequencies are fx = fy = 140 kHz, and fz = 30 kHz for a trapping beam power 2 mW, and the temperature is around 35 µK, i.e. below the Doppler limit. In order to progress towards quantum gates and atom-atom entanglement, we have sent another trapping beam at a small angle in the same optics, in order to trap two atoms at a controlled distance, that can be easily adjusted in the range 1-10 µm.

Various ways to couple the two atoms can then be envisioned, such as a Rydberg state scheme inspired from a proposal by the Innsbruck group [3, 4], or a scheme for "conditional quantum logic", where an arbitrary unitary operation (i.e. a CNOT gate, a Bell measurement...) is realized on a pair of trapped atom (the two qubits), upon the detection of a single scattered photon (the trigger) [5], or a scheme based on cold collisions.

As an alternative, "all-solid-state", approach to quantum information processing, we will describe how a single colored center embedded in a diamond nanocrystal can be used to implement a very simple single photon source, that we have used to carry out a full quantum key distribution protocol [6].

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Recent Progress in Quantum Teleportation with Photonic Qubits

Abstract:

Some recent experimental progress and fruther possibilities in quantum teleportation of qubits stored in photon polarization will be discussed. These results allow to (a) identify more than one Bell state, (b) teleport entangled photon states with high quality, (c) obtain teleprotation without post-selection, and (d) improve quantum teleportation over large distances

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Daily Program

Tuesday 25

Breakfast: 7:30 a.m.

M. Brune 8:30 - 9:05
Measurements of the Wigner Function with Rydberg atoms in Cavity QED

G. Rempe 9:05 - 9:40
Individual Atoms and Photons in Cavity QED

V. Vuletic 9:40 - 10:05
Cooling and slowing of atoms in an optical cavity

A. Hemmerich 10:05 - 10:30
Laser Cooling without spontaneous photons

Brunch / SPORTS: 10:30 - 16:00

A. Imamoglu 16:00 - 16:35
Quantum dot single photon source: prospects for applications in quantum information processing

M. Bayer 16:35 - 17:10
Control of electrons and photons on nanoscale - problems and perspectives

F. Haake 17:10 - 17:35
In between ideal resonators and overdamping: dynamics of overlapping modes

G. Hackenbroich 17:35 - 18:00
Random Lasers

Conference Dinner

Measurements of the Wigner Function with Rydberg atoms in cavity QED

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We have measured the Wigner function W of the vacuum and of a one photon field prepared in a high Q cavity. We implement a method proposed by Lutterbach and Davidovich [1]. The field state is prepared in a superconducting microwave cavity and measured by a single circular Rydberg atom which is strongly coupled to the cavity mode [3]. An analysis of the measured Wigner function allows to reconstruct efficiently the actual photon number distribution of the prepared field.

The Lutterbach-Davidovich method relies on an expression of the Wigner function due to Cahill and Glauber [4] which expresses the Wigner distibution in term of the average value of the parity operator P. Measurement of the parity operator relies on the dispersive atom-field interaction which results in light shifts of the atomic frequency. When the atom crosses the cavity, the atomic state accumulates a phase shift which is proportional to the photon number. This phase shift is measured by Ramsey interferometry. If the atom-cavity interaction time is adjusted so that the single photon phase shift is π , the algebraic contrast of the Ramsey fringes signal is directly the average value of P.

The measurements clearly demonstrate the expected negativity of W when we prepare the one photon state. We make a quantitative analysis of the data by fitting the photon number distribution on the measured values of W. The measurements allow to completely characterize the prepared states.

The direct extension is the measurement of field states with a definite phase such as a small coherent field or a superposition of zero- and one-photon states. This is within the reach of the experiment in its present state. A more demanding goal in term of cavity damping time is the measurement of W for larger photon number Fock states as well as for Schrödinger cat states of the cavity field [5]. This should be made possible by using an improved cavity which is presently in construction.

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Individual Atoms and Photons in Cavity QED

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A single atom at rest and strongly coupled to a single mode of a high-finesse optical cavity is a close-to-ideal quantum system for both fundamental investigations and applications [1]. For example, cavity QED systems are unique in the sense that they allow one to observe and control a single moving atom in real-time with unprecedented spatial and temporal resolution. Indeed, a recent experiment has demonstrated that it is possible to manipulate the motion of a single intra-cavity atom by means of feedback [2]. The feedback led to a significantly longer storage time, limited by random momentum kicks from the near-resonant light field employed. An improved version of the experiment therefore requires a far-detuned dipole trap [3] and a cooling mechanism like the one proposed by Horak et al. [4] and Vuletic et al. [5]. To achieve these goals, we are now applying two laser fields, one far-detuned for trapping and the other with a near-optimal frequency for observing and cooling. First experimental results show trapping times exceeding 100 ms, more than 10 times longer than the average trapping time measured in the dipole trap alone, and several 100 times longer than achieved previously in a near-resonant light field [6, 7]. This constitutes the first clear observation of cavity-mediated cooling.

Cavity QED systems will also find an exciting application in the processing of quantum information, where they might constitute the key ingredient of a distributed quantum network with stationary atoms as quantum memories and flying photons as quantum messengers [8]. In fact, a strongly coupled atom-cavity system can serve as an interface between light and matter. An important step into this direction has recently been made by the realization of a novel light source emitting a sequence of single-photon pulses on demand into a well-defined mode of the radiation field [9]. In the experiment, the photons are produced by an adiabatic passage technique without atomic excitation [10]. The photon generation process is therefore intrinsically reversible – an essential requirement for a quantum network. To measure the properties of the single-photon pulse, one can use the fact that the duration of the light pulse is longer than the resolution time of a typical photon-counting detector. Hence, the pulse amplitude can be determined by standard photon counting techniques. Moreover, an estimate of the phase evolution of the pulse can be obtained by beating it with a suitable local oscillator, e.g. another single-photon pulse. In a first experiment with two consecutively emitted photons interfering on a beam splitter, we have observed a perfect anti-correlation for detection events occurring within a short time interval at the two output ports of the beam splitter, but a reduced effect for larger detection-time differences. The perfect anti-correlation demonstrates the robustness of second-order interference against phase and frequency fluctuations of the emitted photons – an interesting result for all-optical quantum information processing [11].

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Cooling and Slowing of Atoms in an Optical Cavity

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Abstract

We report on collective-emission-induced forces acting on Cs atoms inside an optical cavity. Cs atoms are collected in a magneto-optical trap and dropped along the axis of a vertically oriented, confocal cavity. Two horizontal, counterpropagating laser beams, red detuned from the Cs D_2 transition by an amount δ_a, illuminate the falling cloud. During this process, above a threshold atomic scattering rate, we observe laser emission into the resonator. Forces that deccelerate and cool the atoms accompany the laser emission.

At red laser detunings $|\delta_a| \leq 200$ MHz, comparable to the excited state hyperfine structure, we observe stopping and cooling of 90% of the atoms to temperatures as low as $7\mu K$, well below the atomic and cavity Doppler widths. We have measured that the system exhibits optical gain at frequencies shifted from the incident beam frequency by the atomic center-of-mass Doppler effect and by the Zeeman effect. The laser emission occurs at the frequency of maximum optical gain.

At laser detunings as large as $\delta_a =$ -2.5 GHz, collective emission has also been observed. In this case the spectrum of the optical gain depends only on the velocity of the atoms. The scattering rate per atom into the cavity increases by as much as a factor of 1000 over the single-atom cavity scattering rate. Even at these large detunings, a slowing of the falling cloud is observed.

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Laser Cooling without Spontaneous Photons

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Experiments are reported that demonstrate an efficient laser cooling mechanism which applies to arbitrary polarizable particles like atoms or molecules. The cooling effect emerges via collective coherent scattering inside a far off-resonant optical lattice enhanced by a high finesse (F=180000) ring cavity. Together with tight trapping in the optical lattice potentials (well inside the Lamb-Dicke regime), a favorable combination of low final temperatures and high densities is obtained.

In our experiments the cavity is pumped bidirectionally from a stabilized diode laser source with a power of 1 microwatt and a detuning of 0.7 nm with respect to the D2 line of rubidium. The far-off resonant optical standing wave produced inside the cavity is loaded with about 1 million rubidium atoms at a temperature of 100 microkelvin by a magneto-optic trap (MOT). After several ten ms a flash of near resonant light of typically 100 microseconds duration is applied along the radial direction which yields a fast temperature drop and a corresponding light pulse emerging from the resonator.

"Quantum dot single photon source: prospects for applications in quantum information processing."

Abstract: A single quantum dot can provide a sequence of optical pulses that contain one-and-only-one photon. I will review the properties of these sources and discuss their relevance for the recent proposal for implementing efficient quantum computation using linear optical elements, single-photon sources, and high-efficiency photo-detectors.

Atac Imamoglu

control of electrons and photons on nanoscale - problems and perspectives

Manfred Bayer
Experimentelle Physik II, Universität Dortmund

During recent years intense research efforts have been undertaken to control the properties of electrons and photons in semiconductors in detail. Such a control is an indispensable prerequisite for the realization of novel concepts for quantum optics or quantum information processing. The goal of this talk will be to give some overview of the current status of these activities. In particular, problems and potential solutions will be discussed.

In between ideal resonators and overdamping: dynamics of overlapping modes

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Recent experiments on lasers with bad chaotic resonators and lasing from random media without mirrors require revision of resonator theory, to allow for modes whose spectral widths γ exceed their spacings Δ. The coupling between inside and outside electromagnetic fields can then no longer be treated perturbatively and yields a Lindblad type master equation for the inside modes, as long as no overdamping is incurred.

Employing a basis formed by eigenmodes of the corresponding closed resonator one finds spectral overlap manifest not only in $\gamma > \Delta$ but, more surprisingly, in dissipative mode-mode coupling, i. e. a matrix $\gamma_{\mu\nu}$ of damping coefficients.

The status of the master equation relative to the near-ideal-cavity limit and to the opposite extreme of overdamping will be discussed, and comparisons to other approaches will be given.

Random Lasers

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Random lasers are a novel type of lasers realized in strongly disordered dielectric media. Examples for random lasers include disordered semiconductors, polymer systems, and solutions of TiO_2 nanoparticles. The feedback in these lasers is provided by the random scattering of light in a dielectric with a spatially fluctuating refractive index.

Random lasers differ from conventional lasers in two fundamental aspects. First, while standard laser cavities are defined by mirrors no such mirrors are required for random lasers. As a result, light in random lasers is only weakly confined so that such lasers typically support a large number of overlapping modes. Second, the modes of standard lasers often have a simple spatial structure while random laser modes generically form complicated patterns that reflect the chaotic nature of disordered or wave–chaotic media. Random laser theory therefore must address lasing in wave–chaotic weakly confining laser "resonators".

I summarize our recent theoretical results on random lasers and show that fundamental properties of these lasers can be understood by combining concepts from quantum optics with methods and ideas from quantum and wave chaos.

Daily Program

Wednesday 26

Breakfast: 7:30 a.m.

P. Pillet 8:30 - 9:05
Photoassociation and cold molecules: formation and trapping

M. Weidemüller 9:05 - 9:40
Interactions in a mixture of optically trapped lithium and cesium

J. Javanainen 9:40 - 10:05
Photoassociation and feshbach resonance in a BEC

H. Stoof 10:05 - 10:30
Atom-Molecule Coherence

Brunch / SPORTS: 10:30 - 16:00

M. Lukin 16:00 - 16:35
Engineering quantum phases of ultra-cold atoms in optical lattices

P. Fedichev 16:35 - 17:10
Strongly correlated atomic systems

P. Horak 17:10 - 17:35
Fibre-optic cavities for the observation of single guided atoms

W. Zwerger 17:35 - 18:00
BCS- to Bose-crossover in ultracold Fermigases

Dinner: 18:00 - 19:30

POSTER: 19:30 - 21:00

Photoassociation and cold molecules: formation and trapping

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Photoassociation of ultracold atoms followed by spontaneous emission opens a way for the achievement of samples of ultracold molecules [1]. The efficiency of ultracold ground-state molecules depends on the branching ratio between bound-bound (formation of ultracold molecules) and bound-free (dissociation) transitions for the excited photoassociated molecules [2]. Long-range states in particular below the dissociation limits 6s+6p of the cesium dimer present several schemes with Condon points at intermediate distances, offering efficient channels for the formation of molecules in the ground state or in the lowest triplet state [3]. Temperatures of the obtained molecular cloud are measured in the 10-200 µK range, and formation rates up to 0.2 cold molecule per second and per atom are obtained experimentally in the case of a magneto-optical trap [2].

Accumulating the cold molecules formed in the lowest triplet state inside a magnetic trap offers the possibility to realize a sample with a relatively large number of molecules. A mixed atomic and molecular trap, constituted by a Cs vapor cell magneto-optical trap (MOT) and a quadrupolar magnetic Cs_2 trap has so been performed by using a high magnetic field gradient. The accumulation inside the trap has been demonstrated for 2 10^5 molecules formed via a 200 ms photoassociation process, in the lowest triplet state at a temperature of 30 µK. The life time of the trapped molecular cloud is of the order of one second, mostly limited by the residual vacuum [4]. Possibility of using a light dipole trap will be discussed. Selecting the ground-sate molecules in a well-defined ro-vibrational level will be analyzed in the case of use of stimulated Raman photoassociation processes [5].

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Interactions in a mixture of optically trapped lithium and cesium

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We investigate interaction processes in a gas of ultracold lithium and cesium atoms, which are simultaneously stored in a quasi-electrostatic optical dipole trap (QUEST). The QUEST [1] provides an ideal environment for the study of interaction processes between different atomic species in the electronic ground state since the trapping potential only depends on the static polarizability of the particles [2]. The combination of Li and Cs is of particular interest. Because of the low temperatures that can be achieved by optical cooling, Cs is an ideal cooling agent for sympathetic cooling of the fermionic and bosonic Li isotopes. Furthermore, the heteronuclear dimer LiCs (electric dipole moment ~5 Debye) may be formed in its ground state by photoassociation of cold Li and Cs. We present our results on ground-state interactions and thermodynamics in a binary mixture of Li and Cs, which have revealed surprising effects in the Li-Cs interactions [3]. We discuss the prospects of LiCs photoassociation and show recent experiments on high-resolution photoassociation spectroscopy of optically trapped cesium.

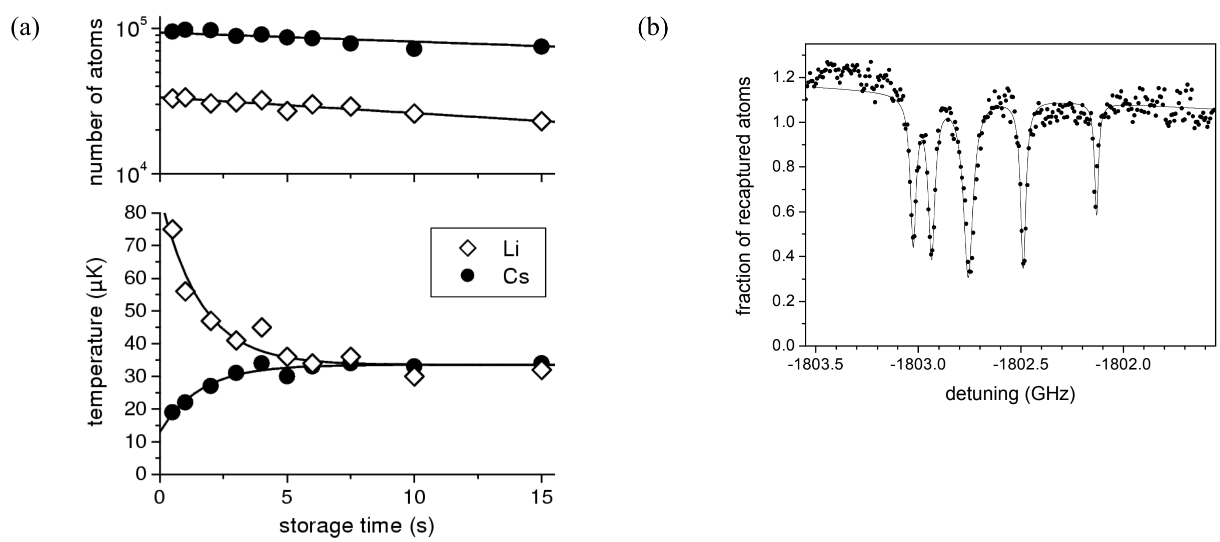

Fig. 1. (a) Loss-less sympathetic cooling of optically trapped lithium (open diamonds) by laser-cooled cesium (closed circles). (b) Photoassociation spectrum of the $Cs_2(0_g$, v=10) state with resolved rotational structure. Shown is the fraction of trapped atoms after 3 seconds of interaction with the photoassociation laser as a function of detuning from the Cs *D2* line.

* Work performed in collaboration with M. Mudrich, S. Kraft, J. Lange, K. Singer, M. Staudt, R. Grimm (Universität Innsbruck), and A. Mosk (FOM-Instituut Rijnhuizen).

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PHOTOASSOCIATION AND FESHBACH RESONANCE IN A BEC

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We discuss the mathematically equivalent theories of photoassociation and Feshbach resonance in a Bose-Einstein Condensate. We include modes for atomic and molecular condensates, noncondensate atoms, and pair correlations between the latter. Collisional quenching of the molecules is also considered. The theory is solved numerically. Predictions include a density dependent limit for the rate of molecule formations that is more stringent than the unitarity limit of collision theory, and rapid adiabatic passage of the atomic condensate to a molecular condensate that works when the magnetic field is swept across the Feshbach resonance in a certain direction but not with the opposite-going sweep. We describe our attempts to reach a quantitative agreement with the Feshbach resonance experiments of Carl Wieman's group.

Atom-Molecule Coherence

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Abstract

We present the appropriate microscopic Hamiltonian for an atomic gas near a Feshbach resonance. We show that this Hamiltonian incorporates both the binding energy of the molecules and the scattering properties of the atoms exactly. Since this is achieved at the quantum level, and not at the mean-field level as in previous approaches, the theory can be immediately applied to both the normal and superfluid phases of trapped atomic Bose and Fermi gases. We discuss a number of such applications in detail.

Engineering quantum phases of ultra-cold atoms in optical lattices

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We will discuss how recently demonstrated techniques for controlling cold atoms in optical lattices could be used for "engineering" quantum phases and quantum correlated atomic states. In particular, we will show that confinement in optical lattices can be used to dramatically enhance superfluidity of fermionic atoms. Similar techniques can be used to accurately study quantum magnetic interactions, to investigate the effects of dissipation on quantum phase transitions and to "engineer" exotic quantum phases of many-body systems. Such systems can probe fundamental problems in many-body physics such as the origin of high temperature superconductivity.

Strongly correlated atomic systems.

Experiments with ultracold atoms in optical lattices offer an interesting possibility to study strongly correlated systems of atoms in the very well understood regime of low densities and interactions between the atoms.
Using the fact that in low dimensional systems the interaction can alter statistics of excitations we show a number of examples of both systems of bosonic and fermionis showing a range of phenomena from spin-density separation and Kondo-effect to quantum Hall effect states.

Fibre-optic cavities for the observation of single guided atoms

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We investigate a variety of designs to use standard fibre technology for optical access to atoms trapped in miniaturised magnetic traps on the surface of silicon or glass substrates.

The main advantage of optical fibres for atom detection or manipulation is the tight transverse confinement of the guided modes. Typically, the waist of a light beam emerging from the end of a single-mode fibre is of the order of a few microns, which is about a factor of ten smaller than the waist of light modes in present cavity QED experiments. Thus the effective interaction of an atom with a single photon is increased by two orders of magnitude. We therefore find that fibre-based cavities provide strong coupling to single atoms even for relatively modest mirror reflectivity. As an example, we discuss single-atom detection by such devices.

First, we investigate theoretically the properties of a standing wave cavity [1]. The cavity consists of two fibre pieces with Bragg mirrors or reflective coatings on one side of each fibre with the non-reflecting ends facing each other. The gap of several microns between the two fibres is large enough to accommodate an atom micro-trap or guide. The cavity is resonantly driven by a laser through one of the mirrors and the transmission through the other mirror is measured. A drop in the cavity output indicates the presence of an atom in the gap, as shown in figure 1(a). We find that a mirror reflectivity as low as 97-99% is sufficient for the detection of single atoms with good signal-to-noise ratios and with only a few photons scattered spontaneously by the atom during the detection time. This also holds taking into account atomic motion and momentum diffusion under realistic conditions in a trap.

Another possibility consists of a ring cavity built out of a 2x2-port fibre coupler where one input and one output fibre are coupled to each other via a small gap. In this case the additional counter-propagating mode creates a range of additional effects. We have found that, in contrast to the standing-wave cavity, a ring-cavity is very sensitive to the actual size of the gap, i.e., whether the gap itself together with the Fresnel reflection at the fibre ends forms a resonant or off-resonant micron-sized cavity, see figure 1(b) and (c). Optimising the ring cavity parameters leads to single-atom detection efficiencies which are similar to those of the standing wave cavity.

We have realised a fibre-coupler ring cavity and a standing-wave cavity with gold mirrors on 2cm lengths of fibre. We measured the loss in the gap as a function of gap size and verified that it behaves as predicted. The finesse of these first efforts was limited by internal losses in the coupler respectively by the quality of the gold mirrors. With improved reflectivity a finesse of 100 or more seems achievable in both cases. Another effort was a standing-wave cavity built with two gold-coated gradient index (GRIN) lenses. This has the advantage that the focusing effect of the lenses allows much larger gap sizes (of the order of 100 μm) without excessively large losses. On the other hand, it is much more difficult to obtain single transverse mode operation in such a system. The highest finesse in the GRIN-lens cavity is limited by the reflectivity of the gold coatings and is again of the order of 100.

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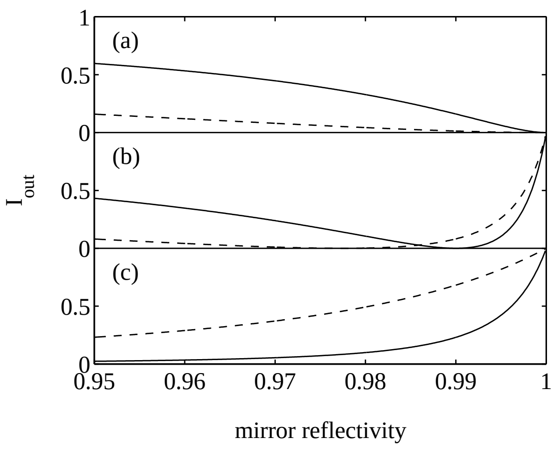

Figure 1: Intensity of light transmitted through the cavity without an atom (solid lines) and with an atom (dashed lines) versus mirror reflectivity. The size of the cavity gap containing the atom is about 7.3 μm. (a) Standing wave cavity with resonant gap. (b) Ring cavity with resonant gap. (c) Ring cavity with off-resonant gap. In all cases the atom is resonant with the pump light. Cavity frequency and atomic position are chosen to maximise the change in cavity output.

"BCS- to Bose-crossover in ultracold Fermigases"

Abstract: In the light of the recent realization of a highly degenerate and strongly interacting gas of Fermionic ^6Li-atoms (K.M.O'Hara et.al. Science 298, 2179 (2002)),

we discuss a simple model which describes the crossover from a weak coupling BCS-superfluid of Cooper-pairs with a size much larger than the interparticle spacing to a Bose-Einstein-condensate of strongly bound Fermionic pairs. Using a coherent state path integral formulation, it is shown in particular that there is a repulsive interaction between the pairs of purely statistical origin.
It is described by an effective dimer-dimer scattering length in three dimensions which turns out to vanish in the Bose-limit. In an effectively 2d situation, however, the repulsion between dimers due to the Pauli-principle of its constituents remains finite even at very strong coupling. Regarding simple experimental signatures of the transition to the superfluid state of Fermionic atoms in a harmonic trap, it is shown that even with moderately strong attractive interactions where k_F |a| is of order one, the transition is associated with only rather small changes in the density and momentum distribution.

Wilhelm Zwerger

Daily Program

Thursday 27

Breakfast: 7:30 a.m.

J. Cubizolles 8:30 - 9:05
Quantum Degenerate Fermi and Bose Gases

S. Stringari 9:05 - 9:40
Effects of superfluidity in trapped fermi gases

M. Baranov 9:40 - 10:05
Superfluid transition in trapped dipolar Fermi gases

P. Törmä 10:05 - 10:30
Josephson effect and Bloch oscillations in atomic fermi-gases

Brunch / SPORTS: 10:30 - 16:00

I. J. Cirac 16:00 - 16:35
Entanglement creation in multiparticle systems

H. Briegel 16:35 - 17:10
Entanglement purification of cluster- and similar multi-party entangled states

M. Plenio 17:10 - 17:35
Entanglement manipulation in continuous variable systems

G. Raithel 17:35 - 18:00
Cold Rydberg atoms new venues in quantum information

Dinner: 18:00 - 19:30

POSTER: 19:30 - 21:00

Quantum Degenerate Fermi and Bose Gases

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Ultra-cold mixtures of Fermi and Bose gases confined in magnetic or optical traps offer unique opportunities to study interacting quantum gases. Several groups have now reached quantum degeneracy with Fermi gases at temperatures down to 0.1 to 0.2 of the Fermi temperature T_F [1–6]. One of the major goals of this research is to observe the transition to a superfluid phase [7], the analog of the superconducting (BCS) phase transition in metals [8]. Very low temperatures and strong attractive interactions in a two-component Fermi gas are favorable conditions to reach this superfluid state.

In dilute gases atomic interactions at low temperature are described by a single parameter, the s-wave scattering length, a. This quantity can be tuned near a Feshbach resonance where the sign and magnitude of a can be adjusted at will by an external magnetic field. Near such a Feshbach resonance, the BCS transition temperature has been theoretically predicted to be as high as 0.25-0.5 T_F, a temperature range which is experimentally accessible [9].

We will discuss recent experiments performed with fermionic ^{6}Li which possesses a Feshbach resonance at convenient magnetic fields. A new experimental approach to measure the interaction energy of a two component Fermi gas near a Feshbach resonance will be described. It reveals that the ^{6}Li $|F = 1/2, m_F = +1/2\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ mixture can be made strongly interacting; Indeed, near the peak of the Feshbach resonance the attractive interaction energy can reach one third of the kinetic energy of the trapped gas [10]. This makes this atom a good candidate for searching for BCS pairing [6, 10] in a conventional optical dipole trap or in an optical lattice [11].

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Sandro Stringari

Effects of superfluidity in trapped Fermi gases

Abstract

I will discuss possible signatures of superfluidity in trapped Fermi gases. These include the dynamics of the expansion, the behaviour of the collective oscillations, rotational effects (moment of inertia and quantized vortices) and Josephson like effects. I will also point out analogies and differences between such systems and cold normal Fermi gases in the collisional regime.

Superfluid transition in trapped dipolar Fermi gases

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(2)Institut für Theoretische Physik, Universität Hannover, D-30167 Hannover, Germany

We study the superfluid phase transition in a system of trapped identical fermions interacting dominantly via dipole-dipole forces and show how the trap anisotropy influences the possibility of the transition and the value of the critical temperature. We also discuss low energy collective excitations in both the normal and the superfluid phases of the gas and indicate a clear experimental way to identify the superfluid transition.

Josephson effect and Bloch oscillations in atomic Fermi-gases

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[2]Department of Physics, University of Jyväskylä, P.O.Box 35, FIN-40351 Jyväskylä, Finland

We consider an analog of the internal Josephson effect in superfluid atomic Fermi-gases. Four different hyperfine states of the atoms are assumed to be trapped and to form two superfluids via the BCS-type pairing. We show that Josephson oscillations can be realized by coupling the superfluids with two laser fields. Choosing the laser detunings in a suitable way leads to an asymmetric below-gap tunneling effect for which there exists no analogue in the context of solid-state superconductivity.

We also discuss the possibility of Bloch oscillations for cold fermionic atoms in optical lattices. We consider atoms in the normal and in the superfluid state.

Entanglement creation in multiparticle systems

F. Verstraete(1), T. Cubitt(1), W. Dür(2), M. Popp(1), J.J. Garcia-Ripoll(1), and J. I. Cirac(1)

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(2) Ludwig-Maximillian Universität, Theresienstr. 25, Munich, GERMANY

The process of entanglement between particles usually takes place through their interaction with a third system. In this contribution we will show how it is possible to entangle two systems, A and B, via their interaction with a third system, C, which remains at all times disentangled from A and B. We will explain this phenomenon in terms of the properties of certain multiparticle states. We will also analyze the role of entanglement in spin systems, and we will make a connection between this property and the correlation functions which are usually studied in Stastical Mechanics.

"Entanglement purification of cluster- and similar multi-party entangled states"

Hans Briegel, LMU Munich

Abtract:
Cluster states have been shown to be the central resource in the one-way quantum computer. In this talk, we show how cluster states can be purifed by a multi-party purification protocol, which is remarkably robust against local noise. The protocol generalizes to (a subclass of) so-called graph states, including the GHZ states and a variety of quantum error correcting codes.
As a consequence, the class of states that are purified is useful both for quantum computation and for multi-party communication.

Entanglement manipulation in continuous variable systems.

Daniel E. Browne [1], Jens Eisert [2], **Martin B. Plenio** [1], Stefan Scheel [1]

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[2] Institute of Physics, Universität Potsdam, Potsdam Germany

Originally, the development of the formal apparatus of quantum information theory assumed finite dimensional systems such as the paradigmatic qubit. In recent years however the entanglement properties of infinite dimensional systems such as harmonic oscillators or optical field modes have received considerable attention. Indeed, field modes of light feature a number of advantages concerning their experimental manageability compared to other quantum systems: For optical systems, both reliable sources producing quantum states and efficient detection schemes such as homodyne detection are experimentally readily available. Quantum states can also be manipulated in an accurate manner by means of passive optical elements such as beam splitters and phase plates. In fact, it has been realized that such systems – often referred to as continuous-variable systems – offer a promising potential for realistic quantum information processing. Indeed quantum teleportation for continuous-variables have been proposed theoretically and experimentally implemented, the generation of entanglement has been studied and cryptographic schemes have been suggested. These investigations complement the original studies of information science in the finite-dimensional regime.

In this talk I will introduce the basic notions of entanglement in continuous variables and motivate the basic questions that are being studied in this area. I will then address the particular problem of entanglement distillation in continuous variable systems. I will review some results that have been obtained by us and other groups and will finish by presenting some of the most recent work from Imperial College.

Georg Raithel

Cold Rydberg atoms – new venues in quantum information

The convergence of laser-cooling and trapping techniques with traditional Rydberg atom spectroscopy has opened up a new and wide-open frontier with implications in quantum information processing, cold-plasma physics, high resolution spectroscopy, and the study of novel atomic systems. Utilizing cryogenic atom traps, we have made several forays into these areas.

Laser-cooled neutral atoms, with temporary excitation to Rydberg states, have been proposed as a platform for quantum computing. I will discuss our efforts to realize a microscopic “dipole blockade” in a cold Rydberg atom gas. This (coherent) mechanism may become an important tool in neutral-atom quantum information processing and mesoscopic entanglement. I will further discuss the (incoherent) dynamics that occurs due to various types of collisions in cold Rydberg gases and plasmas. We observe electron trapping, l-mixing and n-mixing collisions, and full-scale ionization. Experiments in which we study the role of black-body radiation in these systems are underway. An update on experiments that aim at the trapping of Rydberg atoms in conservative magnetostatic, electrostatic, and ponderomotive potentials will be given. Trapped Rydberg atoms are expected to become a powerful tool in high-precision spectroscopy and fundamental measurements. Finally, the physics of exotic, highly magnetized Rydberg states will be discussed, which – as we believe - will play an important role in strongly magnetized cold plasmas. I will describe a superconducting atom trap that we have built in order to extend cold-plasma research into the domain of very high magnetic fields.

Daily Program

Friday 28

Breakfast: 7:30 a.m.

E. Polzik 8:30 - 9:05
Optically coupled atomic ensembles:from continuous variables to cat states to distributed quantum networks

M. Fleischhauer 9:05 - 9:40
Ultra-sensitive Sagnac interferometry with dark-state polaritons

W. Ertmer 9:40 - 10:05
Coherence in Atomic Ensembles

J. Schmiedmayer 10:05 - 10:30
Atom Chips: Mesoscopic Physics with cold atoms

Brunch / SPORTS: 10:30 - 16:00

H. C. Nägerl 16:00 - 16:35
Bose-Einstein condensation of cesium

M. Holland 6:35 - 17:10
Feshbach resonances and collapsing Bose-Einstein condensates

C. Henkel 17:10 - 17:35
Condensate dynamics in noisy magnetic microtraps

R. Ballagh 17:35 - 18:00
The topological atom laser

Dinner: 18:00 - 19:30

POSTER: 19:30 - 21:00

Optically coupled atomic ensembles: from continuous variables to cat states to distributed quantum networks

B. Julsgaard[y] *, J.Sherson*[y]*, W. Tittel*[y]*, P.Petrov, D. Kosec*[y]*, J.Mikkelsen*[y]*, J.L.Sorensen*[y]*, S.Massar*[yy]*, and E.S.Polzik**
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QUANTOP – Danish National Research Foundation Center for Quantum Optics

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Free space optical off-resonant interaction of light with multi-atom ensembles has been proven a fruitful approach towards quantum state engineering and quantum information processing. The first experiments [1] following proposals [2] have demonstrated entanglement of separate macroscopic atomic objects and partial quantum memory. These experiments have been carried out with room temperature atomic gases. Continuous Gaussian variables, such as collective spin of an atomic ensemble and Stokes parameters of an optical pulse have been used for entanglement and other operations. Proposals for atomic teleportation with continuous variables [2], including teleportation of entangled atomic spin states [3] have been put forward.

In a recent development, a scheme for generation of long lived atomic coherent superposition states (cat-states) via light-atoms interaction has been proposed [4]. A proposed implementation of the scheme involves a series of quantum measurements on light propagating through a dense ensemble of $10^3 – 10^4$ ultra-cold atoms.

We have started investigating the quantum coupling of light to cold Cesium atoms trapped in a MOT. Initial experiments show that we are sensitive to the atomic number at the level of $\sqrt{N}$, which is the required benchmark sensitivity. Two consecutive measurements of the atomic number produce nearly identical results proving the non-demolition character of the measurement.

Cat states generated off-line together with linear operations have been earlier proposed as the basis for a new quantum logic scheme [5]. Our proposal provides a possible implementation for this approach. Atomic ensembles prepared off-line in coherent superposition states and coupled via already demonstrated light-atoms quantum interface may become a promising scheme for a distributed quantum networking and computing.

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Ultra-sensitive Sagnac interferometry with dark-state polaritons

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Matter-wave gyroscopes have by now surpassed laser-based devices due to their much larger sensitivity to rotation per unit area. The Sagnac phase shift per unit area A of a matter-wave gyroscope

$$\frac{\Delta\phi_{\rm mat}}{A} = \frac{2\Omega}{\hbar/m} \tag{1}$$

is orders of magnitude larger than that of a laser interferometer

$$\frac{\Delta\phi_{\rm light}}{A} = \frac{4\pi\Omega}{c\lambda} \tag{2}$$

with Ω being the angular velocity. The biggest obstacle however is still the very limited area achievable in matter-wave devices. We here propose and analyze a laser – matter-wave hybrid interferometer using slow light in an atomic vapor. Here the simultaneous transfer of coherence *and* momentum between light and matter via dark-state polaritons is used to create mutually coherent matter waves with large enclosed area and to transfer the accumulated Sagnac phase shift back to light for detection. This leads to a substantially enhanced sensitivity to rotation. The momentum transfer is essential as it will be shown that contrary to intuition a reduction of the group (or phase) velocity alone does *not* result in any change of the Sagnac phase shift. To analyze the sensitivity of the interferometer taking into account center-of-mass motion and momentum transfer the propagation of dark-state polaritons with second-quantized matter-waves is discussed.

Coherence in Atomic Ensembles

W. Ertmer, J. Arlt, G. Birkl, E. Rasel

The production and manipulation of coherent atomic ensembles has enabled much of the most recent progress in cold-atom physics. A number of experiments at Hannover University therefore investigate this key aspect of atomic coherence properties.

We will present our recent progress towards quantum information processing and integrated atom optics with microfabricated optical elements and our measurements of the coherence length of strongly elongated Bose-Einstein condensates. Time permitting, we will also report on our progress towards the realization of quantum degenerate ensembles of metastable Neon and a path towards large scale coherence in alkaline earth samples.

The use of microfabricated optical elements is complementary to recent progress with microfabricated magnetic structures. Microfabrication enables us to tailor optical dipole potentials to the exact shape needed for applications in quantum information processing and guided-atom interferometry. We will present our results on a two-dimensional quantum storage array with up to 80 sites and integrated geometries for guided atom interferometers.

However, recent measurements in our laboratories also show the limits of coherent storage in quantum degenerate samples. We will be presenting our interferometric analysis of spatial phase variations in highly elongated rubidium Bose-Einstein condensates. These measurements point towards general limitations of coherent storage and transport due to very low energy excitations.

Atom Chips: Mesoscopic Physics with cold Atoms

Jörg Schmiedmayer
Physikalisches Institut, Universität Heidelberg

In mesoscopic quantum electronics, electrons move *inside* semiconductor structures and are manipulated using potentials where at least one dimension is comparable to the de-Broglie wavelength of the electrons. Potentials at similar scale can be created for cold neutral atoms moving microns *above* surfaces using microscopic charged ($\mathrm{V} = -\frac{1}{2}\alpha E^2$), current carrying ($V = -\vec{m} \cdot \vec{B}$) or light based (U~α(ω)I) structures fabricated on to a surface. Such devices are called Atom Chips. The simplicity and versatility of these principles will allow us to miniaturise and integrate atom optical elements into matter wave quantum circuits, similar to mesoscopic quantum electronics but ith much longer coherence times [1]. This approach to manipulating atomic matter waves promises to combine the best of two worlds: The ability to use cold atoms - a well controllable quantum system with al the methods known from quantum optics and atomic and molecular physics, and the immense technological capabilities of nano fabrication and microelectronics, known from present day integrated circuit and integrated optics technology, to manipulate the atoms. It holds great promise in implementing controlled coherent evolution on bottom up built mesoscopic quantum systems and quantum information processing. In this talk I will present the basic design principles of such mesoscopic atom optics, discuss its challenges and describe our progress towards extensive control over the internal and external degrees of freedom of neutral atoms. Recent highlights include BEC on an atom chip, atom matter wave fibres that can guide atoms in any direction on a surface, and state selective combined interaction traps. Big challenges are the question of coherence of cold atoms (T<1 μK) close to warm surfaces and how to detect single atoms state (qubit) selectively on the chip in an integrated detector.

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Bose-Einstein Condensation of Cesium

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We report on the realization of a Bose-Einstein condensate with Cesium atoms in the absolute ground state (F=3, m_F=3) [1]. A condensate of approx. 20000 atoms is formed in an optical dipole trap in combination with a magnetic field gradient for gravity compensation (*levitation*) by means of evaporative cooling.

The interaction between ultracold Cs atoms in the (3,3) ground state, represented by the s-wave scattering length, shows a marked dependence on magnetic field strength. A combination of several Feshbach-resonances at low magnetic fields allows one to tune the scattering length over a wide range from large negative to large positive values.

We have investigated the influence of the scattering length on the mean field energy of the condensate. We are able to realize imploding, exploding and "frozen" condensates. Further experiments regarding the formation of molecules near Feshbach resonances and regarding the condensate dynamics at extreme scattering lengths are thus possible.

This work is supported by the Austrian Science Fund (FWF) within SFB 15 (project part 16).

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Feshbach resonances and collapsing Bose-Einstein condensates

Murray Holland

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Feshbach resonances have opened the way to controllable interactions in dilute gases. They have been successfully observed in Bose and Fermion gases in numerous experimental realizations of quantum degeneracy. The ability to tune the interactions allows a range of phenomena to potentially be explored. From the theoretical perspective, the presence of resonances requires a delicate treatment including effects which would lead to a breakdown of the conventional perturbation theory of the dilute gas.

This problem can be applicable to the recent experiments probing the collapse of Bose-Einstein condensates due to the mechanical instability which can emerge when the interactions are attractive. In this talk I will discuss the hidden role of the Feshbach resonance in the collective dynamics when used for achieving a negative scattering length. Utilizing a Feshbach resonance is important as an experimental technique in order to be able to map out the dynamics of collapsing Bose-Einstein condensates. The motivation for this work is in particular the experiments in the laboratory of Carl Wieman at JILA in Boulder, where a burst of atoms and jets were seen to emerge from the collapsing cloud.

The subject has received considerable attention in the field already, for example, through the use of the Gross-Pitaevskii equation with phenomenological three-body loss. However, it is worth revisiting since a complementary recent experiment in the same laboratory showed coherent oscillations between condensates of atoms and molecules when the scattering length was large and positive. This experiment exhibited similar signatures in the development of burst atoms with energies which were larger than that of the condensate, but low enough to remain trapped. The theoretical understanding of this experiment which we were recently able to provide has motivated us to consider similar key concepts in the context of the collapsing condensate system with scattering length large and negative.

Condensate dynamics in noisy magnetic microtraps

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Germany

Recent experiments with miniaturized surface traps have shown that condensates are an extremely sensitive probe of trapping field fluctuations. The main signatures are trap loss, heating and decoherence.
We review theoretical estimates for the corresponding rates and discuss recent results where relatively weak fluctuations lead to a collapse of the condensate phase coherence. Implications for integrated interferometers and quantum gates are outlined.

The topological atom laser

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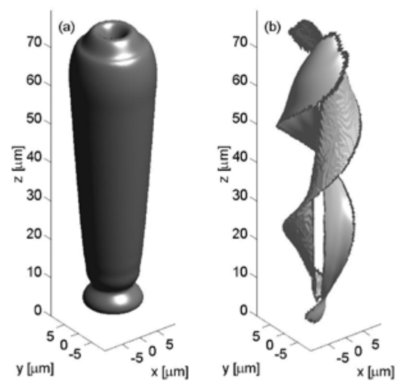
One of the goals of atom optics is to engineer matter waves with specific phase and density spatial profiles, and Bose-Einstein condensates with their large scale coherence provide a natural starting point. Atom lasers based on output coupling from a condensate in the ground state have produced well collimated waves with essentially plane-wave phases. In this paper we calculate the properties of matter waves output from a condensate in a topologically excited state. In our model, atoms from a trapped topological condensate state, such as a vortex, are coherently transferred by a Raman coupling scheme into an untrapped hyperfine state which can propagate freely away from the trapped atoms. The system is treated in a meanfield approximation using coupled Gross-Pitaevskii equations, for which we obtain both numerical and analytic solutions, with the latter being valid in the linearised regime. In the example of a trapped vortex, the propagating output field may take on a variety of topological features, depending on geometry and Raman parameters. For the case where the output beam is transverse to the vortex core, we find that a sequence of Raman pulses can produce a sequence of vortices propagating in the direction of the Raman momentum difference, with a relative phase between vortices determined by Raman parameters. A continuous Raman pulse produces a continuous output beam, scattered preferentially from one or other side of the vortex depending on the Raman detuning. For the case where the scattering direction is parallel to the vortex core, the output beam is a hollow cylinder, analogous to the TEM_{01} mode of an optical laser, but with helical phase twist, as illustrated in the figure. The analytic solution allows us to determine the resonance condition for the output coupling, and to characterize the phase properties of the output wave. For example we show that the helicity of the phase twist for the case in the figure is controlled by the Raman detuning.



Output matter wave at t = 1.4 ms from a 2.2×10^5 atom ^{23}Na vortex condensate. (a) density iso-surface; (b) 0 and π phase iso-surfaces.