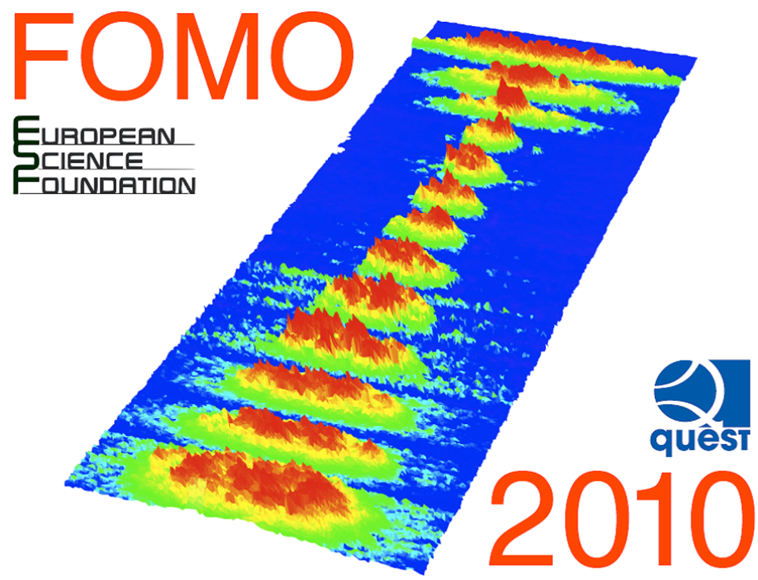

Frontiers on Matter Wave Optics

Crete, April 6-11

Book of Abstracts

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Test of gravitation with quantum objects

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Abstract

This talk is about a test of gravitation at small distances by quantum interference deep into the theoretically interesting regime of 10000 times gravity [1]. The method allows a precise measurement of quantum mechanical phase shifts of a Schrödinger wave packet bouncing off a hard surface in the gravitational field of the earth. The experiment is sensitive to gravity-like forces at a length scale below 10 μm, where we already place limits. Such forces can be mediated from gauge bosons propagating in a higher dimensional space and this experiment can therefore test speculations on large extra dimensions of sub-millimetre size of space-time or the origin of the cosmological constant in the universe, where effects are predicted in the interesting range of this experiment and might give a signal in an improved setup.

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A simplified fiber-based high-power diode laser system

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Abstract

Since the advent of semiconductor lasers in the 1960s, they have found many applications in various fields of research. In the majority of experiments in this field, semiconductor diode lasers are used in an extended cavity diode laser (ECDL) configuration [1, 2] which offers a large mode-hop free range, increased lasing power and decreased line-width. Due to the increasing complexity of laser cooling and BEC experiments, there is a need to provide a substantial amount of optical power to the various aspect of the experiment, such as cooling, re-pumping, imaging and optical pumping beams. Many ECDL lasers cannot provide adequate power to perform such tasks simultaneously. Therefore, an optical amplification system needs to be implemented in order to increase the optical power available for the experiment while maintaining the optical properties such as line-width and beam quality.

The main focus of this poster will be on a novel amplification system, which is based on operating a semiconductor tapered amplifier in a novel double-pass configuration. This results in a 1 W semiconductor tapered amplifier to output 600 mW of usable power from a low power seed beam of 0.5 mW while still maintaining the parameter of the injection light.

As well as this novel amplification technique, a complete laser system suitable for BEC experiments with Rb atoms will be described. This will include the locking of an ECDL Littrow configuration laser system to hyperfine atomic transitions using a Doppler-free saturated absorption spectroscopy technique. Another important technique employed is the rf modulation [3, 4, 5] of a slave laser diode at 6.8 GHz which stimulates the Rb-87 re-pumping transition necessary for laser cooling.

This work is a ongoing endeavor and in are currently investigating incorporating the rf modulation described above, into a high power tapered laser system.

Keywords: diode laser, tapered amplifier, microwave generated repumper

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Diffusion of ultra-cold atoms in an disordered pancake potential

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Abstract

When confined in two dimensions, numerous intriguing disorder related phenomena affect the transport properties of electrons in solid state systems. Recently, disorder-related phenomena started to be experimentally explored in atomic ultra-cold gases. Here, we present experimental results on diffusive expansion of an initially trapped 87Rb ultra-cold gas, confined along the vertical direction, in presence of an anisotropic disordered potential. Our experiment is a first step towards the study of other disorder effects in two dimensions, from anomalous subdiffusion [1] and classical trapping under the percolation threshold [2] to Anderson localisation [3].

The confinement in the horizontal plane is realized between the two lobes of a TEM01 blue-detuned beam [4,5], vertically focused and transversally collimated. The disordered potential is created by a speckle field [6], generated by a diffusive plate. We observe planar anisotropic diffusion of the low energy atoms and simultaneously ballistic expansion of the high energy atoms. After long expansion times, we extract quantitative informations on the energy dependence of the diffusion constants from the comparison of the observed density profiles with a diffusive model.

Keywords: Ultra-cold atoms, Disorder, Diffusion

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Dispersive phase shifts due to atom-surface interactions

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Abstract

We used the Toulouse atom interferometer to study how Van der Waals (VdW) interactions between atoms and surfaces cause velocity-dependent phase shifts for atomic de Broglie waves [1]. By introducing a thin nano-grating in one branch of this interferometer, we observed a phase shift (see Figure 1) that depends on velocity to the power -0.49. This dispersion serves to measure both the strength and the position dependence of the atom-surface potential in the range from 5 to 10nm from the surface, and it can also set new limits on non-Newtonian gravity in the 2 nm range.

Related work is described in references [2, 3]

Keywords: Nanostructures, atom interferometry, van der Waals

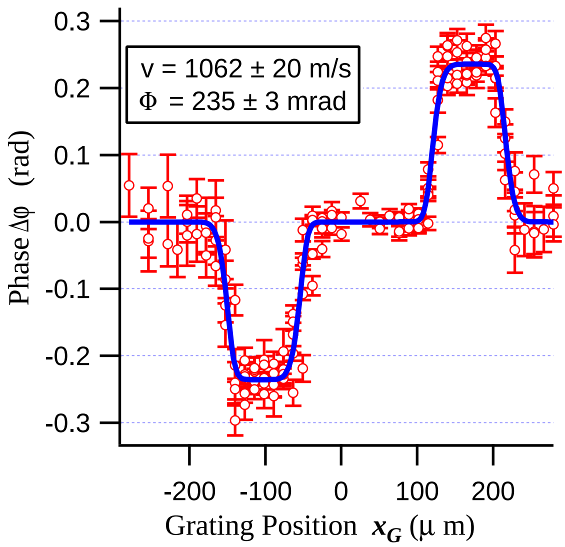

Figure 1: Measured phase shift $\Delta\varphi$ due to transmission through a nano-grating. Phase shift data are shown as a function of the interaction grating position x_G, for a lithium beam velocity $v = 1062 \pm 20$m/s. At the reference position, $x_G = 0$, both interferometer arms go through the gap, so they are unaffected by the grating. When $65 < |x_G| < 190$ μm only one arm goes through the grating and we observe opposite phase shifts. When $|x_G| > 190\mu$m both arms go through the grating, the phase shift returns to 0. The best fit is represented by the continuous line and the parameter Φ.

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New applications for nano-gratings

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Abstract

Nano-gratings offer several advantages for matter-wave optics [1]. For example, in Arizona we diffract electrons, molecules, and atoms. Because these particles pass within 25 nm of a nano-grating bar, we can study particle-surface interactions.

For electrons we used nano-gratings to build a Talbot interferometer [2] and a Lau interferometer [3]. We made these by adapting a scanning electron microscope and inserting two nano-gratings. Fringes from these interferometers were used to study electric fields around samples, wave-front radii of curvature for electron beams, transverse coherence lengths for electron beams, and electron-surface image-charge interactions. Surprisingly, a nominally 2 nm thick Au/Pd coating - not even enough to make a macroscopically measurable conductivity - mitigates charging enough so that silicon nitride nano-structures can serve as gratings for coherent electron optics.

For atoms, we use nano-gratings as beam-splitters for a Mach-Zehnder interferometer. We use beams of Li, Na, K, Rb, Sr, He*, or Ar* in the same apparatus. Recently we measured the ground state DC polarizability for Na, K, and Rb atoms, each with an uncertainty of 1.0%, and an uncertainty in the ratios (e.g. $\alpha_{\mathrm{Rb}}/\alpha_{\mathrm{Na}}$) of 0.3% [4].

Atom diffraction was used to measure atom-surface van der Waals C_3 coefficients for Li, Na, K, and Rb with 3% uncertainty in the ratios. These data support predictions that core electrons contribute 17% to C_3 for Rb atoms and a silicon-nitride surface. This compares to only 4% for Na atoms.

In collaboration with the Toulouse group we measured atomic de Broglie wave phase shifts that result from atoms passing through a nano-grating [5]. These phase shifts were measured precisely enough to test the power law for the atom-surface potential, to set new limits on non-Newtonian gravitational interactions between the atoms and the nano-grating, and to observe the predicted $v^{-0.49}$ velocity dependence.

Keywords: Nanostructures, electron holography, atom interferometry, polarizability, van der Waals

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Parametric amplification of matter waves in dipolar spinor Bose-Einstein condensates

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Abstract

In this presentation we analyze the spinor dynamics in spinor Bose-Einstein condensates (with particular emphasis on the Rb87 F=1 case). Starting from an initial condensate in the Zeeman state m=0, the initial stages of the dynamics are characterized by a correlated pair creation into m=+1 and -1 which closely resembles parametric amplification in quantum optics. This coherent dynamics is induced by spin-changing collisions, which having a very low energy scale associated, are very sensitive to other small energy scales. In particular, as we shall discuss in detail in this presentation, the spinor dynamics is shown to be largely modified by the weak magnetic dipole-dipole interactions. We analyze in detail the dipolar effects (in particular the modification of the parametric amplification dependening on the magnetic-field orientation) and how these effects are extremely sensitive with respect to even rather weak magnetic field gradients in the experiments. In the last part of this presentation, we shall discuss the formation of spatial patterns in the parametrically amplified clouds in m=+1 and -1.

Entanglement and decoherence within neutron interferometry

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Abstract

Fundamental quantum properties like quantum coherence and entanglement are amoung the most interesting features of quantum mechanics which are studied nowadays. They form the basis for the new, fast developing fields of quantum information and computation.

The physical system of interest is the (massive) neutron subjected to interferometric and polarimetric measurements. Neutrons are proper objects for a study of quantum mechanical behavior: they allow for rather easy experimental control and the neutron spin is the simplest two-level system which can be manipulated by magnetic fields. In combination with interferometric measurements the system has enough intrinsical richness to show interesting quantum features such as entanglement.

The coupling of the neutron to an external magnetic field allows for selective manipulations of the spinor quantum states. This can be used, on the one hand, to create entangled states where the entanglement occurs between different degrees of freedom (e.g., spin and path) and, on the other hand, one can introduce dephasing and decoherence by varying magnetic fields.

Decoherence arises in quantum systems which can not be perfectly isolated from the surrounding environment. We are faced with a modification of the state of the system described by an effective master equation. In choosing different Linblad generators for the master equation it is possible to study different decoherence modes for a two qubit system.

We investigate different kinds of entanglement for the neutron system and mechanisms for decoherence and dephasing. Especially we propose an experimental realization of several decoherence modes within neutron interferometry where the sources of decoherence are fluctuating magnetic fields [1]. In particular we study the effects of decoherence for maximally entangled states and Schrödinger cat states [2].

The time dependent solutions for different decoherence modes are depicted in the so-called spin geometry picture which allows to illustrate the evolution of the (nonlocal) correlations stored in a certain state [3].

Keywords: neutron interferometry, entanglement, decoherence

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Molecular Dynamics and Structure in Interferometry

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Abstract

Kapitza-Dirac-Talbot-Lau interferometry (KDTLI) has been successfully established as a well-adapted tool for studying the wave nature of massive and complex molecules [3].

De Broglie coherence is to first order only associated with the center-of-mass motion. In the presence of external perturbations, quantum metrology however also becomes highly sensitive to internal molecular properties, such as electric susceptibilities or dipole moments, which may affect the interference contrast or phase shift without introducing genuine decoherence. Molecular structure or internal dynamics determine the electric properties and become accessible through KDTLI.

We present recent experimental data from interference experiments showing the influence of molecular dynamics on de Broglie coherence [1].

In addition, high-contrast interference measurements now show for the first time the possibility to distinguish two structural isomers, i.e. two sorts of perlfuoralkyl-functionalized molecules with the same mass (1592 amu) and the same chemical sum formula, in molecule interferometry [2].

Keywords: MATTER WAVE INTERFEROMETRY, METROLOGY, MOLECULAR PHYSICS

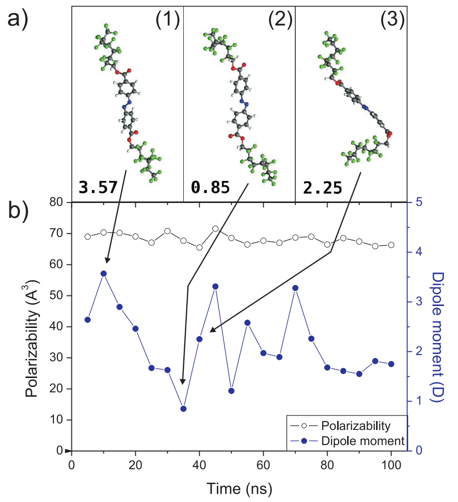

Figure 1: a) Snap shots of the simulation of perfluoroalkylated azobenzenes at 10 ns (1), 35 ns (2), and 40 ns (3). b) Static scalar polarizability, α_{stat} and electric dipole moment d along the MDS trajectory.

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Towards a lattice based neutral magnesium optical frequency standard

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Abstract

Magnesium is an interesting candidate for a future high performance neutral atom optical frequency standard. It offers low sensitivity to frequency shifts of the $^1S_0$ to $^3P_0$ clock transition by room temperature blackbody radiation and several isotopes of suitable abundance (two bosonic, one fermionic) to realize an optical clock. In order to reach long spectroscopic times and therefore high resolution, it is necessary to perform spectroscopy on optically trapped atoms. For neutral atom optical clocks, it is possible to trap atoms in an optical lattice at the magic wavelength, where both states of the clock transition experience the same light shift due to the trapping field and can also be confined to the Lamb-Dicke regime.

In this contribution, we report on the recent progress on the neutral atom magnesium frequency standard. We established a 73 km fiber link, which connects the Mg experiment (IQ, Hannover) to the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig) to enable the comparison of the Mg frequency standard to PTB's high performance optical frequency standards. With this fiber link, we compared two ultrastable lasers at IQ and PTB on the 10^{-15} level in fractions of a second. This fiber link was also used to determine the stability and absolute frequency of the current setup of the Mg frequency standard, which probes cold free falling atoms on the $^1S_0$ to $^3P_0$ transition.

On the other hand, we are studying trapping of Mg in an optical dipole trap as a step towards a lattice-based frequency standard. Atoms are precooled in a two-stage MOT. The second MOT has a decay channel to the dark 3P0 state. All cooling stages are running continuously and atoms are accumulated in a 1064 nm optical trap. Routinely, we trap up to 910^4 atoms at a temperature below 100 K with this technique.

In the next step, we plan to implement an optical lattice and measure the value of the magic wavelength, which is theoretically predicted at 470 nm.

Keywords: MAGNESIUM, MG, OPTICAL CLOCK, LATTICE CLOCK, CLOCK, FREQUENCY STANDARD UND METROLOGY

Matter wave interferometry as a tool for molecule metrology

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Abstract

Talbot-Lau interferometry has recently been established as an ideal method to perform quantum matter wave experiments with large, highly polarizable molecules in the so far inaccessible mass range of beyond 1000 atomic mass units [1]. We will address benefits, challenges and potential limits of matter wave experiments with very massive objects.

Especially for thermally excited, complex molecules with a rich structure and dynamics, the interaction between their internal motion and their center-of-mass motion has often been considered as a serious obstacle for de Broglie interferometry. We present ways how information about the internal molecular properties can be extracted in matter wave experiments without destroying the quantum interference.

Specifically, by combining Talbot-Lau matter wave interferometry with optical phase gratings and external electric deflection fields, we were able to get a quantitative measure of total electric susceptibilities, including static polarizabilities and dipole moments, as well as optical polarizabilities since these properties significantly influence both, the visibility and the phase shift of the resulting interference patterns.

From these data we could then derive statements about the origin of molecular fragmentation [2], demonstrating that molecular interferometry may serve as a useful complement to mass spectrometry.

Furthermore, we could reveal the existence of thermally activated dipole moments in otherwise non-polar molecules [3] and we could show that quantum interferometry may well distinguish constitutional isomers, i.e. molecules of equal mass and equal chemical sum formula but with a different internal atomic arrangement, in spite of the fact that de Broglie interferometry is describing delocalized center of mass wave functions only.

Keywords: MATTER WAVES, INTERFEROMETRY, METROLOGY, DECOHERENCE

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Decoherence and Collisional Frequency Shifts

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Abstract

A novel frequency shift due to collisions of fermions was recently observed in an optical lattice clock [1]. The shift was surprising since identical fermions cannot scatter at low temperature and previous arguments suggested that even distinguishable fermions could not produce a collision shift [2]. For bosons and fermions, the conventional wisdom has been that frequency shifts are proportional to the difference of chemical potentials and therefore also the partial densities of the clock states. We theoretically analyze Rabi and Ramsey spectroscopy of trapped fermions and show that the collision shift for fermions is not proportional to the difference of partial densities. Instead, when two fermions in non-identical superpositions collide, one fermion gets a positive frequency shift and the other a negative frequency shift. In Ramsey spectroscopy, when the second pulse is a $\pi/2$ pulse ($\overline{\Theta}_2 = \pi/2$ in Fig. 1), the frequency shift of both atoms is probed with the same sensitivity and there is no shift [3]. For other pulse strengths, the two shifts largely cancel. We show that the behavior for Rabi excitation is essentially identical. This problem has subsequently been treated by two other groups [4, 5]. Their explanations are consistent with the conventional wisdom that collisional frequency shifts are proportional to the difference of partial densities. We will describe the shift and discuss the discrepancies of the treatments. We will also discuss the factor of 2 controversy for bosons[6] and the confusion that arises from an over-simplified view of energy conservation.

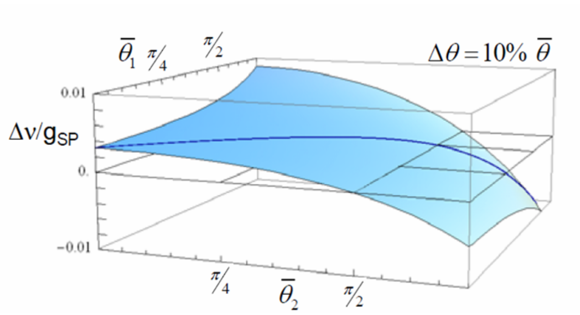

Figure 1: Frequency shift due to fermions collisions as a function of the Ramsey pulse tipping angles, $\overline{\Theta}_1$ and $\overline{\Theta}_2$. The shift is not proportional to the difference of partial densities $n_P.n_S$, which would imply a strong dependence $\overline{\Theta}_1$. The shift does vary strongly with the second Ramsey pulse area, going to 0 if the second pulse is on average a $\pi/2$ pulse. The solid line is the shift for the usual case of equal pulses.

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Quantum phase transitions in 1D systems

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Abstract

Phase transitions can occur in quantum systems even at a temperature of absolute zero. Unlike in thermodynamics, those quantum phase transitions are not driven by thermal fluctuations but by quantum fluctuations and connect two ground states of the system. A well known example in a deep lattice potential is the Mott-Hubbard quantum phase transition from a weekly interacting superfluid to a Mott insulating phase. However, for a strongly-interacting quantum system confined to one-dimensional geometry a novel type of quantum phase transition may be induced by adding an arbitrarily weak optical lattice potential commensurate with the atomic granularity [1]. We observe this so called commensurate-incommensurate quantum phase transition for a one-dimensional quantum gas of bosonic cesium atoms with tunable interactions, connecting the phases of a Tonks-Girardeau gas and a Mott-insulator.

Keywords: Bose-Hubbard, sine-Gordon, Mott-insulator, Tonks-Girardeau gas, 1D,

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Atomic Fresnel Biprism

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Abstract

It is possible to take advantage of the transverse coherence of a standard supersonic atomic beam and a large longitudinal coherence length due to slow velocities, for which the atomic "de Broglie" wavelength gets into the nanometre range. Such a slowed atomic beam fills then the gap between the extremely well velocity - defined supersonic beam and the large atomic wavelength of "cold atom" beam. A usual Zeeman slower configuration allows us to change the speed of the atoms from 560m/s to a few tens of m/s [1]. Such an unusual atomic source is presently under study and will be used for atom - surface experiments, typically in the nanometres range.

The first new experiment that will be done is based on an efficient coupling between atomic Zeeman states (for atoms with internal angular momentum) allowed by the quadrupolar component of the surface-induced van der Waals (vdW) interaction [2]. This exo-energetic "vdW - Zeeman" transition provides a tuneable (magnetic field intensity dependent) beam splitter that we theoretically illustrate by the simplest possible interferometer: an atomic counterpart of the Fresnel biprism [3]. The velocity - adjustable atomic beam is here coming across two opposite surfaces (single slit of a nano-grating, see figure 1). For a large enough transverse coherent radius, the atom wave packet will be strongly inelastically diffracted by the two opposite surfaces at some distance from the slit to yield non localised interference fringes. The calculation has been done for Ar* metastable atoms with a grating of 100nm period and different velocities of the atoms (560 to 10 m/s). *Via* the interference pattern (Schlieren image), this device should give access to such novel information as the oscillating part of the complex vdW - interaction transition amplitude. This simplest configuration is not sensitive to inertial effect. As a next step, a loop - closing transmission grating will be added to realize a new type of compact closed interferometer. The experiment is presently in progress.

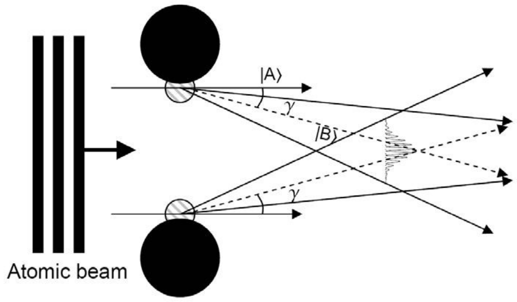

Figure 1: The atomic Fresnel biprism interferometer principle. γ is the angular deviation induced by the passage from the |A> to the |B> magnetic sub-level

Keywords: coherent atom optics, Fresnel biprism, van der Waals-Zeeman transitions

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Negative refraction of matter waves

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Abstract

The extension of "left-handed" optical metamaterials to negative-index media (NIM) for matter waves is a topic of particular importance [1]. Since V.G. Veselago [2], many works have been devoted to optical NIM's and their properties (negative refraction, perfect focussing, reversed Doppler Effect, cloaking, etc.). Such artificial media are essentially characterised by a negative value of the optical index, *i.e.* the reversal of the wave vector $\vec{k}$ with respect to the Poynting vector $\vec{R}$. What should be the "de-Broglie optics" counterpart [1]? To the energy flux corresponds the current density of probability, or equivalently the group velocity $\vec{v_g}$. Therefore, one has to reverse $\vec{v_g}$ with respect to $\vec{k}$, *i.e.* the phase velocity. However, contrarily to light optics where $\vec{R}$ remains directed outwards whereas $\vec{k}$ is directed towards the light source [3], for matter waves the direction of the phase velocity is unchanged, whereas $\vec{v_g}$ is now towards the source [1]. Such an effect is necessarily transient. Our approach relies on position- and time-dependent magnetic potentials [1]. A novel class of potentials - "*comoving*" potentials [2] - provides us with a remarkably simple solution to devise negative-index media for matter waves [1]. These co-moving potentials are oscillating magnetic potentials which, by an adequate choice of the spatial period and oscillation frequency, can be made co-propagating with the atom wave [4]. The calculation of the induced phase-shift demonstrates the possibility of producing transient negative group velocities for the atomic wave packet (see figure 1). Correlatively to negative refraction, a transient narrowing of the wave packet is obtained, a time-reversal effect which should be usable in atom optics. With an adequate space and time-dependence of the co-moving field, we can also devise cylindrical or spherical "*metalenses*". This opens novel applications in atom nano-lithography and interferometry.

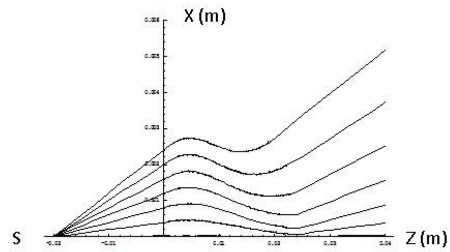

Figure 1: Trajectories of the wave packet center.

Keywords: comoving potentials, negative refraction, atom optics, metalenses

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Optical studies of entanglements in a single-neutron system

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Abstract

Since the early stage of the development, quantum theory is bizarre: in trying to understand it, we had to forgive everything we know about causality, reality, certainty and so on. This is a completely different world, ruled by its own probability law. Neutron interferometry is one of the most suitable strategies to study quantum mechanics, where quantum interference effect of matter waves can be observed in a macroscopic scale. Starting with 4 -periodicity of spinor wave function, quantum phenomena such as gravitational effect on the wave function, superposition of spinor wave function, topological effect in quantum evolutions, were confirmed experimentally. In parallel, by utilizing an interference effect between two orthogonal spin states of neutrons, it turned out that the polarimetric strategy can be used for similar studies. Recently we accomplished neutron optical experiments concerning noncontextual hidden-variable theories, which are a kind of the hidden variable models of quantum mechanics, like local hidden variable theories, trying to give realistic view of quantum phenomena. Entangled states between degrees of freedom in single neutrons are exploited and following experiments are carried out.

- Violations of Bell-like inequalities for spin-path entanglement in neutron interferometer [1] and for spin-energy entanglement in neutron polarimeter [2].
- Two experiments concerning Kochen-Specker theorem[3, 4]
- Quantum state tomography of spin-path entangled Bell-like states [5]
- Triply entangled GHZ-state [6]

I am going to give an overview of these optical experiments with neutrons and discuss their future perspectives.

Keywords: interferometer, polarimeter, entanglement, Bell's inequality, Kochen Spcker theorem, state tomography, GHZ state

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Absolute and ratio measurements of the polarizability of Na, K, and Rb with an atom interferometer

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Abstract

We present absolute and ratio measurements of the ground state electric dipole polarizability of sodium, potassium, and rubidium using a Mach-Zehnder atom interferometer with an electric field gradient (Fig. 1). The uncertainty of each absolute measurement is less than 1.0% and the uncertainty of each ratio measurement is 0.3%. Our measurements (Table 1) serve as improved tests of atomic structure calculations. Please see arXiv:1001.3888 and `www.atomwave.org`

Keywords: polarizability, atom interferometry, sodium, potassium, rubidium

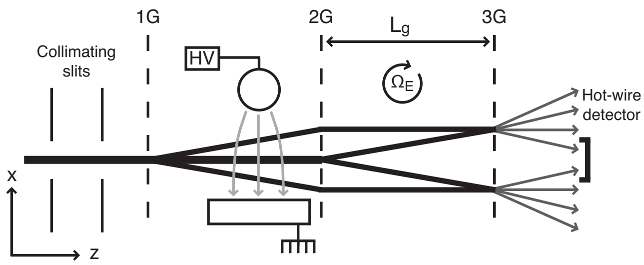

Figure 1: Nanogratings 1G, 2G, and 3G form multiple Mach-Zehnder interferometers (two are shown). An atom passing through the interaction region acquires a phase ϕ_1, ϕ_0, and ϕ_{-1} along each path. The third grating acts as a mask for the 100 nm period interference fringes. The distance between two gratings is $L_g = 940$ mm. The vertical (transverse) scale is exaggerated 10^4 times. The Earth rotation rate Ω_E modifies the measured phase shift.

Table 1: Measured absolute and recommended atomic polarizabilities in units of 10^{-24} cm^3. Recommended polarizability measurements are based on our ratio measurements and the sodium polarizability measurement from reference [1].

	α_{abs}(stat.)(sys.)	α_{rec}(tot.)
Na	24.11(2)(18)	24.11(8)
K	43.06(14)(33)	43.06(21)
Rb	47.24(12)(42)	47.24(21)

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Neutral helium atom microscopy

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Abstract

Surface science has been revolutionized in recent years by nano-resolution imaging techniques such as scanning tunneling microscopy (STM) and atomic force microscopy (AFM). It is often said that the field of nano-technology was born with the invention of the STM in the early 1980s.

In 2008 we presented results using a focussed beam of neutral helium atoms as a microscopy tool[2],[3], creating the first 2D image of an object obtained with neutral matter waves. The imaged object was a hexagonal Cu-grating, and the image was obtained in transmission by scanning across the object. The resolution was about 2 micron, determined by the size of the focussed beam.

Helium atom scattering is already known as a powerful probe for investigating the structural and dynamical properties of surfaces[1]. The two major advantages of using neutral helium atoms in microscopy are 1) the low energy of the helium beam (less than 100 meV for a de Broglie wavelength of 1 Å) and 2) the fact that the atoms are uncharged. This means that a scanning helium atom microscope can be applied with no sample damage and without additional sample preparation such as conductive coating. Hence it should be possible to investigate insulators, biological materials and all fragile samples which are difficult to examine by other methods.

In this paper we present new results demonstrating the first sub-micron focus of a neutral helium beam. The small spot size was created using a free standing Fresnel zone plate as optical element. Furthermore we present our design for a new neutral helium beam reflection scanning microscope, which we are currently in the process of constructing.

Keywords: Molecular Beams, Fresnel Zone Plate, De Broglie Atom Optics, Microscopy

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Bright matter-wave solitons: formation, dynamics and quantum reflection.

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Abstract

What happens to a Bose-Einstein condensate when the atomic interactions are switched from repulsive to attractive? The experimental observations of the collapse of ^{85}Rb condensates reveal the formation of a robust configuration of bright matter-wave solitons or solitary waves that oscillate along the (weaker) axial direction of the trap, colliding repeatedly in the trap centre [1]. We show that, within the framework of the Gross-Pitaevskii equation (GPE), such collisions exhibit a rich behaviour [2] that indicates the need for a π relative phase between neighbouring solitons to explain the stability observed experimentally [3]. However the question remains whether the GPE model accurately captures the essential physics in this case? We describe new experiments planned to address this issue and discuss the application of bright solitons to the study of quantum reflection and the measurement of atom-surface interactions [4].

Keywords: BEC, matter-wave, solitons, GPE, ^{85}Rb

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Probing decoherence and entanglement with molecular systems

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Abstract

The talk will discuss two topics in molecular quantum optics, a field that seeks to apply concepts and methods from quantum optics and quantum information theory to molecular systems. Specifically, I will describe how decoherence due to the interaction with an achiral background gas can explain the super-selection and stabilization of chiral molecular configurations states [1]. In the second part, a proposal to demonstrate non-local correlations in the motion of far separated particles will be presented. It is based on the well-controlled Feshbach dissociation of Li_2 molecules [2], and it would allow one to test quantum mechanical delocalization on unprecedented scales.

Keywords: Hund's paradox, chiral super-selection, dissociation time entanglement, Bell test for atomic motion

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Intermodulation noise in cold atom interferometers

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Abstract

Cold atom interferometers are highly sensitive instruments that can be used to measure different physical quantities very precisely. Example of such instruments developed nowadays in several laboratories are gyroscopes for the measurement of the Earth rotation. These instruments are based on a cold atom fountain geometry where the microwave cavity is replaced by a Raman laser interrogation. Due to their sequential mode of operation, they suffer from a measurement stability degradation which is similar to the Dick effect appearing in pulsed fountain clocks. In the case of fountain clocks, a continuous mode of operation allows one to decrease the residual intermodulation noise to a negligible level compared to the atomic beam shot-noise[1]. For gyroscopes, a continuous operation could be a means of avoiding this stability limitation.

In the frame of the EuroQUASAR program, we investigate how a continuous mode of operation could improve the measurement sensitivity of cold atom interferometers. The goal is to compare the intermodulation noise level to the shot-noise limit of the interferometer. To bring useful results to the EuroQUASAR community, we started by considering the case of the compact dual atom interferometer gyroscope currently developed at the Institute of Quantum Optics of the Leibniz University of Hannover. In a first step, and to keep the model as simple as possible, we studied only the case of a single gyroscope. The model developed for the estimation of the residual intermodulation noise in our continuous fountain clocks[2] has been adapted to a three-zone Mach-Zehnder type interferometer. It takes into account a continuous monokinetic atomic beam that can have any time-dependence of the atom flux (from continuous to pulsed through multiball) making this model very useful to compare continuous and pulsed operations. In our calculations, we consider only the noise sources coming from the Raman frequency and the retroreflected mirror vibrations. To get realistic results, we use the experimental noise power spectral densities measured on the LUH gyroscope. First results show that a pulsed operation of the gyroscope will bring the resulting intermodulation noise level one order of magnitude above the shot-noise limit, the vibrations noise being the limiting factor. By contrast, calculations for a continuous operation with a phase modulation of the last Raman beam show a clear improvement of the stability, the intermodulation noise reaching a level two orders of magnitude below the present shot-noise limit. These first results seem to show clearly the potential stability improvement of a continuous operation. However, these results have been obtained making ideal hypothesis about the Raman pulses and they need to be confirmed for a more realistic modeling of the atom-light interaction and for the case of a dual interferometer.

Keywords: Intermodulation noise, ultimate sensitivity cold atom gyroscope, cold and slow continuous beam, continuous and pulsed operation

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A parametric amplifier of matter waves

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Abstract

Matter wave optics with ultracold samples has reached the point where non-classical states can be prepared and their fascinating properties can be explored. In optics, parametric down conversion is routinely used to generate light with squeezed observables as well as highly entangled photon pairs. The applications of these non-classical states range from fundamental tests of quantum mechanics to improved interferometers and quantum computation. Therefore, it is of great interest to realize such non-classical states with matter waves. Bose-Einstein condensates with non-zero spin can provide a mechanism analogous to parametric down conversion, thus enabling the generation of non-classical matter waves. We observed magnetic field dependent spin resonances [1] where the spin dynamics is enhanced. On these resonances, a parametric amplification process produces entangled matter waves excited spatial modes. We show that this exponential amplification can amplify both classical matter waves as well as vacuum fluctuations to macroscopic clouds [2]. Intriguingly, these spatial modes can carry orbital angular momentum. A first analysis shows that the system may serve as a source of atomic Bell pairs with entangled angular momentum states, possibly allowing for Bell type measurements with neutral atoms.

Keywords: SPINOR BOSE-EINSTEIN CONDENSATES, PARAMETRIC AMPLIFICATION, NON CLASSICAL MATTER WAVES, VACUUM FLUCTUATIONS

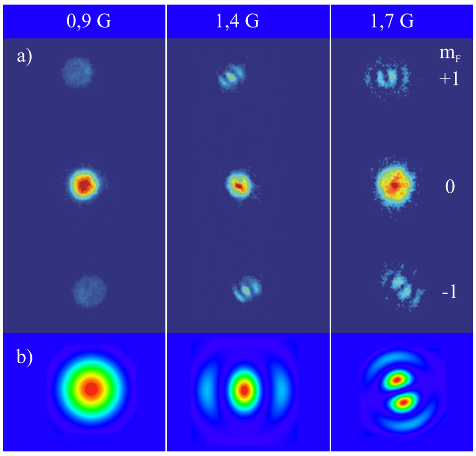

Figure 1: Parametric amplification of excited spatial modes. (a) Absorption images of spinor condensates after the separation of the spin components m_F for specific magnetic field strengths. (b) Spatial distribution from a simple model: ground state (left), radially excited mode (center) and angular momentum mode (right).

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Imaging of trapped single Rb atoms

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Abstract

We report on the trapping, and imaging of single atoms in a magneto-optical trap (MOT). The high localization of cold single atoms [1] has an increasing variety of interests aimed applications ranging from triggered single photon source [2] and photon-atom entanglement [3] to atom strings as a quantum register [4] aiming towards quantum information.

The fluorescence of atoms in low atomic density collected with an APD is used to observe the signature of atoms captured in the trap. An atom entering or leaving the trap will produce a discrete change in the fluorescence level. The discrete steps are thus associated with atoms either being loaded in the trap from background Rb vapour, or from atoms lost due to background gas collisions. A histogram of occurrence of a given count rate is constructed from a long term observation.

The fluorescence of a single atom in the trap is imaged by a CCD for observation times of about one minute at the same time with the APD signal, and the resulting steps are compared with those from the APD.

In the future we indent to use Fourier filtered absorption imaging to image free single atoms released from the trap.

Keywords: single atom, MOT, low atom number detection, immaging

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Towards atom interferometry in microgravity

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Abstract

The research field of cold and degenerate quantum gases offers the possibility to study ideal models for a multitude of fundamental and applied problems in the quantum domain. In recent years, developments of new and versatile trap configurations, the use of various atomic species and mixtures, as well as enlarged accuracy of the applied manipulation methods drastically extended the variety of simulated quantum systems. As a consequence of these efforts atom interferometry was shown to be an appropriate candidate to perform high precision measurements, e.g. to measure inertial forces such as gravity or rotations.

Microgravity promises to substantially extend the science of degenerate quantum gases towards nowadays inaccessible regimes of low temperatures, macroscopic dimensions of coherent matter waves and longer unperturbed evolution. Utilizing this low noise environment for interferometry schemes and applications like inertial quantum sensors with high precision is one of the main goals of the QUANTUS project. As a source for coherent matter waves we use a Bose-Einstein condensate of Rubidium 87, whose ultra-long free evolution of one second in microgravity was already demonstrated at the drop tower in Bremen (ZARM). In order to realize a Mach-Zehnder interferometer we choose Bragg diffraction as a coherent beam splitting process. With this setup we will be able to measure spatial and temporal coherence in the extended parameter regime available during the free fall.

In addition we are working on the second generation apparatus, which combines an extremely compact design and extends the physics observable in microgravity. The experiment is planned to use 87Rb and 40K as degenerate Bose-Fermi mixtures in order to carry out experiments on tests of the Weak Equivalence Principle in the quantum domain. A major experimental challenge is to design a catapult capable experimental setup, which have to withstand 30g accelerations during the catapult launch. In the catapult mode we can prepare and manipulate our wave packets during 9 seconds of microgravity, which substantially increases the interrogation time and therefore the sensitivity of the interferometer.

The QUANTUS project is a collaboration of LU Hannover, ZARM at U Bremen, U Ulm, TU Darmstadt, University of Birmingham, U Hamburg, and HU Berlin. It is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50WM0835-0839

Keywords: BEC, atom interferometry, atomic sensors, Bose-Fermi mixtures, microgravity

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Coherent population trapping and the control of light-induced torque on three-level atoms

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Abstract

There is currently much interest in the interaction of atoms, ions, molecules and Bose-Einstein condensates with laser light endowed with orbital angular momentum, such as those known as Laguerre-Gaussian beams. Such beams can now be readily generated in the laboratory and one of the most striking effects on atomic systems in addition to translational forces is that they impose light induced torques. The light torque was first predicted in 1994 [1] for two-level atoms, leading to the creation of neutral currents as well and electric currents at the nanoscale [2, 3, 4] . Here we show that three-level atoms also experience a light-induced torque whose characteristics depend sensitively on the atomic parameters. The scenario involves two counter-propagating LG beams appropriately detuned from the atomic resonances, creating a torque influencing rotational motion, as well as leading to axial cooling of the atomic motion. We also show that the system is amenable to coherent population trapping [5] and in such a way that it is possible to create conditions in which the torque vanishes. The possible implications of this on the manipulation of cold atoms and condensates is pointed out and discussed.

Keywords:

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Recent progress towards the quantum limit of optical lattice clocks

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Abstract

Optical lattice clocks have already proven to be good candidates for next generation atomic clocks. Due to the atomic confinement, their ultimate accuracy should be comparable to the one of trapped ion clocks. In terms of stability, however, they can potentially outperform their ion counterparts by using a large number of atoms. The main limitation of the clock stability remains the clock laser frequency noise associated with the Dick effect. This limit can be pushed by improving both the laser frequency noise and the duty cycle of the clock.

Regarding the laser noise, we present a new laser locked to an ultra-stable ULE cavity with silica mirrors. This cavity has a low thermal noise thanks to the use of a fused-silica mirror substrate. We show that the relatively high thermal expansion coefficient of silica can be accommodated for with a high performance temperature stabilization of the cavity vacuum chamber down to a few 100 K, and massive passive thermal shielding of the cavity inside vacuum. We demonstrate a laser stability better than 10^{-15} for averaging times up to several tens of seconds.

As for the duty cycle, we have developed a non-destructive detection scheme of the clock transition probability based on a phase measurement of a weak laser beam propagating the atomic cloud. The detection scheme allows us to keep more than 95 % of the atoms in the dipole trap from cycle to cycle, opening up the possibility for vastly reduced loading time and increased duty cycle. We have performed a numerical optimization of the clock cycle that takes into account our experimental parameters, as well as the ultra-stable laser residual noise. A clock stability as low as $2 \times 10^{-16}\,\tau^{-1/2}$ is expected.

To demonstrate this stability one would have to compare the clock with an equally stable second clock. We have constructed a second Sr lattice clock. Several comparison techniques exist between two identical clocks sharing the same clock laser, as is the case for our experiment. We show that the stability when comparing two clocks using the same clock laser, where the interrogation windows are triggered randomly, is at the same level as when comparing two completely independent clocks. Furthermore, it would be possible to interleave the interrogation periods of the two clocks, such that one would simulate a completely dead-time free clock, which would be independent of the clock laser frequency noise, thus reaching the heralded quantum projection noise limit of optical lattice clocks.

Keywords: OPTICAL CLOCKS, OPTICAL LATTICE, QUANTUM NOISE

Detection of the He-McKellar-Wilkens phase shift by atom interferometry

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Abstract

The Aharonov-Bohm effect [1], predicted in 1959, is the first example of a family of topological phase effects [2] which contains also the Aharonov-Casher effect and the He-McKellar-Wilkens (HMW) effect [3], introduced independently by X.-G. He and B.H.J. McKellar and by M. Wilkens for the motion of a constant electric dipole moment interacting with a magnetic field. The case of a polarizable neutral particle considered by H. Wei et al., is closer to an experiment. All these topological phases are independent of the particle velocity.

Following H. Wei et al., the HMW phase shift which appears when an atom propagates in crossed electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$ is given by $\Delta\phi_{HMW} = 4\pi\varepsilon_0 \int \alpha\mathbf{v}\cdot(\mathbf{B}\times\mathbf{E})\, dt/\hbar$. To detect this effect, we must be able to cancel the considerably larger polarizability phase shift equal to $\Delta\phi_{pol} = 2\pi\varepsilon_0 \int \alpha\mathbf{E}^2 dt/\hbar$.

We have built an experiment using our Mach-Zehnder atom interferometer [4] based on a thermal lithium atomic beam and laser diffraction in the Bragg regime which provides high quality signals and a high phase sensitivity ca. 10 mrad/$\sqrt{\text{Hz}}$. The atom propagation is perturbed by a double capacitor with a septum located in between the interferometer arms. The capacitor is placed just before the second laser standing wave, where the arm separation is largest and it creates opposite electric fields $E_m \approx \pm 5\times 10^5$ V/m on the two interferometer arms while a coil create an homogeneous magnetic field $B_m \approx \pm 0.02$ Tesla. The electric field is horizontal while the magnetic field is vertical. The capacitor is as symmetric as possible and we apply slightly different voltages to compensate for the residual asymmetry of the polarisability shift.

The HMW effect should appear as a phase shift which is not the sum of phase shift due to the electric field and of the one due to the magnetic field alone. With our parameters, we expect a phase-shift $\Delta\phi_{HMW} \approx \pm 15$ milliradians. We have already collected a large data set which proves the existence of this phase-shift and we work to improve the accuracy of its measurement, limited by phase drifts. We will soon verify that the HMW phase-shift is independent of the atom velocity.

In conclusion, we have made the first detection of the He-McKellar-Wilkens topological phase shift. This effect is particularly interesting as it modifies the propagation in a non-reciprocal way i.e. the phase sign would be opposite for atoms propagating backwards.

Keywords: He-McKellar-Wilkens phase-shift, atom interferometer, high phase sensitivity

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Advanced laser systems for coherent manipulation of matter waves in microgravity

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Abstract

Targeting a long-term goal of studying cold quantum gases on a space platform, we perform preliminary experiments under microgravity conditions at the ZARM drop tower in Bremen. A sounding rocket mission is planned for the near future. In this context compact and robust laser systems have been developed.

This poster will present the laser system capable of performing dual-species atom interferometry experiments with degenerate Bose-Fermi mixtures of ^{87}Rb and ^{40}K at the drop tower. In particular, we show the concepts of a hybrid integrated master-oscillator power amplifier (MOPA) and a highly miniaturized, spectroscopy stabilized reference laser. The MOPA consists of a DFB laser chip, a tapered amplifier (TA), and micro-optical components, all integrated on a $10 \times 50\ mm^2$ micro-bench. The reference laser combines this micro-bench technology with a mesoscopic vapor cell.

Two different concepts of Raman lasers for coherent manipulation of the wave packets will be shown in detail. The one is basing on a fiber electro-optical modulator (EOM) followed by injection lock of a DFB laser diode. The other one utilizes a double-passed acousto-optical modulator (AOM).

Special challenges in the construction of this system are posed by the drop-tower environment which entails critical vibrations during drop capsule release and peak decelerations of up to 50 g during the launch of the catapult and during recapture at the bottom of the tower. All optical and electronic components have thus been designed with stringent demands on mechanical stability and reliability. These features of the laser system open new routes to quantum optics experiments also on other microgravity platforms, like ballistic rockets or the International Space Station (ISS).

The QUANTUS project is a collaboration of LU Hannover, ZARM at U Bremen, U Ulm, TU Darmstadt, University of Birmingham, U Hamburg, and HU Berlin. It is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50WM0835-0839

Keywords: Laser system, atom interferometry, Bose-Fermi mixtures, micro-integrated optics, microgravity

Ratio measurements of atom-surface potentials reveal effect of core electrons

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Abstract

Van der Waals (vdW) and Casimir-Polder potentials are the dominant interactions between charge-neutral objects at nano- to micrometer length scales. Understanding these potentials is important for designing atom-chips and nanotechnology devices as well as searches for vacuum friction and non-Newtonian gravitational potentials at short length scales.

The contribution of atomic core electrons to vdW potentials is surprisingly large. While core electrons only contribute 3% to the DC-polarizability of Rb atoms, they are predicted to contribute 35% to the vdW potential (C_3) for Rb near an ideal surface [1]. For a silicon nitride surface, the importance of core electrons is still predicted to be about 17%. Until now, no measurements have verified this prediction.

Our data confirm that core electrons are significant for C_3 of Rb atoms and a silicon nitride surface. We measured ratios of C_3 for several different atoms (Li, Na, K, and Rb) and the same surface to highlight the role of core electrons. In absolute measurements of C_3, the effect of core electrons can be masked by other effects such as variation in surface response, contaminations, and edge effects.

By diffracting different species of atoms from the same nano-grating we measured ratios, e.g. $C_3(Rb)/C_3(Na)$, with a precision better than 3%. These ratio measurements are insensitive to surface contaminations and impurities. In addition, no knowledge of the grating geometry or the shape of the potential is required to interpret the diffraction data. Figure 1 shows the measured ratios as well as predictions based on a single oscillator model and a model that includes core electrons.

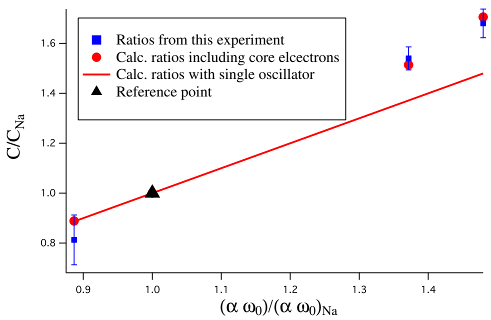

Figure 1: Experimentally determined ratios of potential strength relative to Na (C/C_{Na}) compared to model predictions. For the heavier atoms there is a clear deviation from the single oscillator model and core electrons have to be taken into account.

Keywords: VAN DER WAALS, ATOM-SURFACE POTENTIALS, CORE ELECTRONS, DIFFRACTION

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Rovibronic ground state molecules in an optical lattice

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Abstract

Ultracold samples of molecules are ideally suited for fundamental studies in physics and chemistry. For many of the proposed experiments full control over the molecular wave function in the rovibronic ground state is needed. Our starting point for the creation of groundstate molecules is a Bose-Einstein condensate of cesium atoms, loaded into a 3D optical lattice. Weakly bound molecules are produced by a magnetic field ramp over a Feshbach resonance (Fig. 1). By going into the Mott-insulator state before the association, we assure nearly perfect shielding against inelastic collisions and a high production efficiency. We report on our experimental results on the molecular spectroscopy for all four transitions [1, 2, 3] and the transfer of the molecules to different weakly and deeply bound states [1, 4, 5], especially the rovibronic ground state [5]. We show the properties such as lifetime or polarisibility of the different molecular states in the optical lattice [4, 5] and our final steps towards a Bose-Einstein condensate of rovibronic ground state molecules.

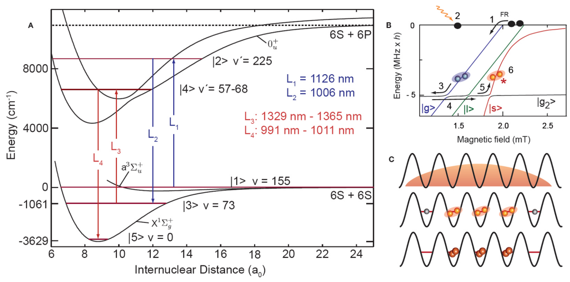

Figure 1: **A** Molecular level scheme for Cs_2. The weakly bound Feshbach level $|1>$ is transferred to the rovibrational level $|3>=|v=73>$ and further to the rovibronic ground state $|5>=|v=0>$ of the singlet $X^1\Sigma_g^+$ potential in the presence of an optical lattice.**B** Zeeman diagram showing all relevant molecular levels for initial Feshbach state preparation. The molecules are produced on a g-wave Feshbach resonance and are then transferred to the weakly bound s-wave state $|1>$ (6) for the STIRAP transfer. **C** Lattice based ground state transfer. Top: The BEC is adiabatically loaded into the three-dimensional optical lattice. Middle: Doubly occupied sites are converted to Feshbach molecules. Bottom: The molecules are transferred to deeply bound rovibrational levels.

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Quantum phase engineering for angular momentum states

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Abstract

Superfluid vortices in Bose-Einstein Condensates have been one of the most interesting topics of research in cold atomic physics in recent years. They are represented by localised defects around which a quantised current is flowing and the associated quantum numbers can in principle be used to represent quantum bits [1]. These quantum numbers are of geometrical nature and they would allow achieving large storage times, since the lifetime of a vortex is often only determined by the topology of the external trapping potential. While the fundamental properties of vortices are well investigated, proposals for detailed state engineering are rare.

Here we will show how a vortex superposition state can be created in a controlled manner. For this we make use of a process related to Stimulated Raman Adiabatic Passage (STIRAP), which in optics is a process that uses a counterintuative sequence of laser pulses to transfer an electron between the two ground states in a lambda system. An analoguous process for the centre-of-mass states for trapped atoms, called Coherent Tunneling Adiabatic Passage (CTAP), has recently been suggested, which allows high fidelity transfer of population densities between spatially separated traps.

Applying this process to a two-dimensional vortex state takes a degree of freedom into account that has no equivalent in the optical case and we find that the non-trivial phase distribution of the vortex gets changed in a complicated but predictible way [2]. In particular we show that the phase distribution of the final state can be adjusted by the experimenter by simply chosing the overall time the CTAP process will take.

This project was supported by Science Foundation Ireland under project number 05/IN/I852.

Keywords: Bose-Einstein Condensates, Superfluids, Vortices, CTAP

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Stability and dynamics of matter-wave vortices in the presence of collisional inhomogeneities and dissipative perturbations

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Abstract

The spectral properties of singly-charged vortices and vortex dipoles in a Bose-Einstein condensate confined in a highly anisotropic (disk-shaped) harmonic trap are investigated. Special emphasis is given on the analysis of the so-called anomalous (negative energy) mode of the Bogoliubov spectrum. We use analytical and numerical techniques to illustrate the connection of the anomalous mode to the precession dynamics of the vortices in the trap. Effects due to inhomogeneous interatomic interactions and dissipative perturbations motivated by finite temperature considerations are explored. We find that both of these effects may give rise to oscillatory instabilities of the vortices, which are suitably diagnosed through the perturbation-induced evolution of the anomalous mode, and being monitored by direct numerical simulations.

*On sabbatical leave from: Nonlinear Dynamical System Group (URL: http://nlds.sdsu.edu), Computational Science Research Center, and Department of Mathematics and Statistics, San Diego State University, San Diego, California 92182-7720, USA

Keywords: BEC, matter-wave, vortices, GPE, collisonal inhomogenity

Exploring the physics of disorder with a Bose-Einstein condensate with tunable interaction

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Abstract

We will report on ongoing experiments on the interplay of disorder and interactions performed with a Bose-Einstein condensate in quasiperiodic lattices. Tuning the atom-atom interaction via a broad Feshbach resonance allows to explore various regimes. For vanishing interaction we observe Anderson localization [1], while an increasing repulsion drives the system first into an insulating Anderson glass regime and finally into a BEC regime, where long range coherence is recovered [2].

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A novel Ioffe Pritchard magnetic trap for BEC in tuneable elongated traps

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Abstract

The experimental demonstration of Bose-Einstein condensation (BEC) is one of the most exciting developments of recent years and has allowed researchers to study quantum effects on the macroscopic scale with well controllable parameters. The current interest of this experiment is to study, for the first time, the time-evolution of the phase of individual BECs. We expect to observe phase decoherence induced by the inherent interaction of the BEC with its thermal cloud. For such an experiment, the number of atoms in the BEC becomes an important figure of merit, given that the decoherence of the phase will manifest itself clearest for large BECs and dense thermal clouds.

One of the major challenges in performing such an experiment is to design an adequate and easy-to-use magnetic trapping system with appropriate trapping parameter to maintain large number of atoms. The focus of this poster will be on a novel configuration Ioffe-Pritchard magnetic trap which is designed to perform such a task. This magnetic trap consists of four pairs of coils which create a cigar-shaped, three dimensional harmonic trap at low energies and a linear trap at higher energies. Also presented in this poster will be the various aspects of the proposed experimental setup which will enhance the number of atoms prior to being magnetically trapped. This will include a 2D MOT section which will be used as a source of cold atom to load a standard six beam MOT resulting in a large number of laser cooled atoms.

Keywords: LIST, OF, KEYWORDS, SEPARATED, BY, COMMAS

Accuracy of a cold atom gravimeter

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Abstract

Atom interferometry allows for realizing inertial sensors (gyroscopes, accelerometers) whose performances are comparable or better than state of the art instruments [1, 2]. Among such sensors, gravimeters cover a broad range of applications, from fundamental physics, metrology and geophysics to industrial related applications, such as navigation and underground prospection .... These perspectives stimulate the research towards higher sensitivity, stability and overall performance of atomic sensors and towards more compact and movable systems.

We will present the cold atom gravimeter realized at LNE-SYRTE in the frame of the watt balance project of the Laboratoire National de Métrologie et d'Essais [3], which aims at both high accuracy and discrete portability, with an interferometer interaction length relatively short, of a few centimeters only. A first prototype of the gravimeter reached an excellent sensitivity of 2×10^{-8}g at 1 s, despite the noisy environment of Paris inner city [4]. Its accuracy was limited by large parasitic shifts, arising from wavefront distortions and insufficient control of the transverse trajectories. A new vacuum chamber has recently been realized to reduce these systematics. The improvements of this second generation setup will be detailed. The results of a first characterization of it will be presented, as well as a preliminary accuracy budget. Comparisons between this atomic gravimeter and "classical" corner cube gravimeters [5] showed good agreement between the sensors at a level better than 10^{-8}g.

Keywords: ATOM INTERFEROMETRY, INERTIAL SENSORS, METROLOGY, GRAVIMETRY

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One-dimensional Bose gases in and out of equilibrium

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Abstract

Dimensionality strongly affect the physics of a Bose gas. Freezing its transverse degrees of freedom allows to enter the one-dimensional regime, characterized by large phase fluctuations for degenerate weakly interacting gases. In expansion, these fluctuations lead to strong density density correlations that we have been able to measure experimentally [1]. Our results show good agreement with a recent theoretical description [2]. Interestingly, our measurements take place in a near field regime where anomalous correlations play an important role.

Even though all the atoms forming a one-dimensional Bose gas lie in their transverse ground state, these degrees of freedom have to be taken into account to accurately describe the dynamics of such systems [3]. Populating their transverse excited states by parametric heating, we have been able to study their relaxation's properties. Due to parity rules the decay by binary collisions of the transverse excitations leads to the creation of pairs of longitudinal high energy free particles with opposite momenta. Using a novel fluorescence detector [4], we have been able to show that the number difference of these modes is squeezed. We now aim to study the longitudinal relaxation of these correlated pairs.

Keywords: LOW DIMENSIONS, CORRELATIONS, SQUEEZING, BOSE GAS

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Superconducting atom chips

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Abstract

Atom chips with micron-sized current-conducting wires realize flexible magnetic traps for laser-cooled atoms. Chips based on superconducting wires are particularly interesting. Extremely long trapping times can be expected, due to the ultra-high vacuum conditions in a cryogenic environment and to the reduced Johnson-Nyquist current noise in the conducting surfaces. These chips open the way to the coupling of atomic samples with mesoscopic quantum circuits and to the deterministic preparation of individual Rydberg atoms for cavity QED experiments [1, 2].

We have realized a superconducting chip set-up [3]. The niobium thin-film wires are coated by a gold surface, used to create in front of the chip a mirror-MOT, which captures a low-velocity atomic beam. The atoms are then transferred to a Ioffe-Pritchard trap resulting from the superposition of a constant adjustable bias field with that created by an on-chip Z-shaped wire.

We have measured the trapping lifetime as a function of the distance from the gold layer. At large distances (400 μm), it is over ten minutes. At a shorter distance (30 μm), it is reduced to $\simeq$40 s, in agreement with predicted atomic spin-flip rate due to the Johnson-Nyquist current noise in the cold normal metal layer [4]. When the atoms are brought close to the superconducting wires underneath the mirror, we observe hysteretic modifications of the trapping potential due to the permanent currents in the superconductor [5]. This observation is promising for the realization of programmable permanent trap structures.

Much longer lifetimes are expected when atoms approach a naked superconducting surface. We have developed a detailed model of the lifetime, taking into account vortex dynamics in the thin film [6]. We predict lifetimes significantly shorter than those obtained in other less detailed models, but still three orders of magnitude larger than for a normal metal at the same temperature. This result is very encouraging for coherent atomic manipulation on superconducting chips.

In these ideal conditions, we readily obtain Bose-Einstein condensation on the chip [7], with about 10^4 atoms in a $30\times1\times1$ μm cigar-shaped volume. A slightly tighter confinement will lead to the deterministic preparation of individual Rydberg atoms using the dipole blockade mechanism. These atoms could then be trapped on chip for coupling to superconducting circuits or on-chip cavity [1]. They can also be Stark-accelerated and launched in 3D very high quality superconducting cavities [2].

Keywords: ATOM CHIPS, BEC, RYDBERG ATOMS

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Comprehensive Control of Atomic Motion

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Abstract

The method of laser cooling has opened the door to low temperature physics of dilute gases. Despite the great success of this method, it has been limited to a very small set of atoms in the periodic table and no molecules. I will describe in this talk new approaches to trapping and cooling that have been developed in my group [1]. The first step uses pulsed magnetic fields to stop atoms and molecules where they can be magnetically trapped. The next step is an experimental realization of informational cooling as first proposed by Leo Szilard in 1929 in an effort to resolve the paradox of Maxwell's demon. Together, these provide a two-step comprehensive solution to trapping and cooling. I will describe the projected impact of this work on physics, chemistry, and technology.

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Splitting a condensate on an atom chip: effect of temperature and interactions

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Abstract

We measure atom number statistics after splitting a gas of $N \sim 1000$ ultracold ^{87}Rb atoms in a purely magnetic double-well potential on an atom chip. Well below the critical temperature T_c, we observe reduced fluctuations down to -4.9 dB below the shot-noise level. Fluctuations rise to more than +3.8 dB close to T_c, before reaching the shot-noise level for higher temperatures. We use two-mode and classical field simulations to model these results. This allows us to confirm that the super-poissonian fluctuations directly originate from quantum statistics.

Poisson's spot with molecules

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Abstract

In the Poisson-Spot experiment, waves emanating from a source are blocked by a circular obstacle. Due to their positive on-axis interference an image of the source (the Poisson spot) is observed within the geometrical shadow of the obstacle. At the beginning of the 19^{th} century the Poisson spot experiment played a crucial role in proving the wave-nature of light[1] and now it is the last of the classical optics experiments to be realized with neutral matter waves.

Here we report the observation of Poisson's Spot using a beam of neutral deuterium molecules (see fig.1). We used a supersonic-expansion beam from a nozzle cooled to a temperature of 101 K. This resulted in a terminal beam velocity of v=1060 ms^{-1}, as determined from time-of-flight spectra, and corresponding to a de Broglie wavelength of λ=0.096 nm. The circular obstacle was a free-standing silicon-nitride disk of 60 μm diameter. We detected the beam using an electron-bombardment ionization detector.

Interesting applications could include the study of large-molecule or cluster diffraction and coherence in atom-lasers. There are a few advantages over grating interferometers that could possibly outweigh the drawbacks from the low-brightness nature of the Poisson spot. One is that the interaction with the matter-wave beam is reduced to a single edge, transmitting even objects that would block a fine grating. Also, constraints on angular alignment and position of the circular obstacle are very weak. Furthermore, the on-axis interference condition for the Poisson Spot is wavelength independent and can therefore utilize the entire velocity and mass spectrum of potential beam sources.

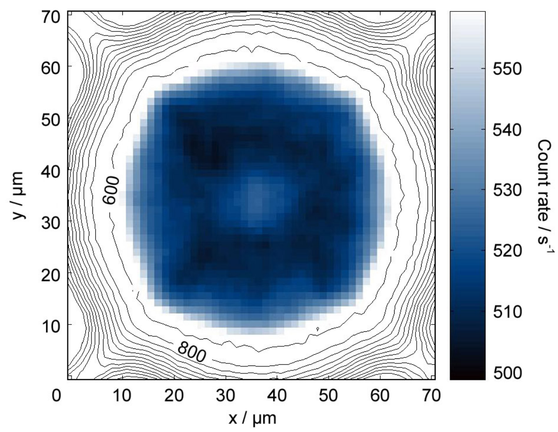

Figure 1: Deuterium matter-waves forming a Poisson spot.

Keywords: POISSON SPOT, DEUTERIUM, FREE-JET EXPANSION

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The application of atom lasers to precision measurement

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Abstract

Atom interferometry with laser cooled atoms has been shown to be a competitive platform for inertial sensors and as a testbed for fundamental measurements. Using laser cooled atoms offers two advantages over hot thermal beams: a smaller velocity width, and hence higher beam-splitting efficiency, and a more compact apparatus for the same enclosed area. In this seminar we will look at using BEC and atom lasers as a source for matter wave interferometry. We will first give an overview of our research into atom laser output couplers [[1]], and discuss our work on pumping [[2]]. With an M^2 value of 1.4 and an instantaneous flux of 10^7 atoms/s in a pure $m_F = 0$ beam, a freely falling atom laser looks to be a good candidate for atom interferometry. In addition to having a narrower velocity width than a laser cooled source, atom lasers offer the possibility of quadrature squeezing as a path to improved signal to noise in a measurement. We will discuss two prototype 'clock state' systems running in our labs. A free space interferometer operating at the projection noise limit with 10^4 atoms [[3]] and a trapped atom system currently limited to a factor of 2.5 off the projection noise limit with 10^6 condensate atoms. I will discuss the technical and fundamental noise sources that limit our current systems, and outline our solutions to these problems.

Keywords: atomlaser, interferometry

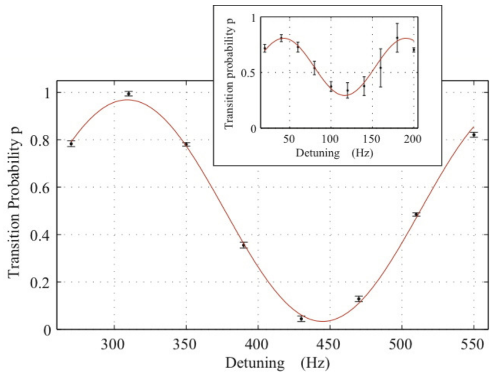

Figure 1: Noise measurement on a Ramsey fringe. The graph illustrates a significant improvement in signal-to-noise as compared to the data in our previous work, Opt. Express **17**, 20661 (2009) (see inset).

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Towards simulation of impurity movement through a Tonks-Girardeau gas

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Abstract

Recent advances in the field of atom cooling and trapping have led to renewed interest in low dimensional quantum systems [1]. In particular, the case of a strongly interacting Bose gas (in the so called Tonks-Girardeau regime) has attracted considerable interest [2, 3].

In a recent experimental paper [4], the movement of a spin impurity through a quasi one-dimensional Tonks-Girardeau gas has been investigated. Impurity atoms are produced by coupling a fraction of the tube of Tonks-Girardeau atoms into an untrapped hyperfine level. This impurity is accelerated through the trapped cloud by gravity. Interesting results have been observed, indicating complex dynamics between the in-trap component and impurity atoms.

In this work, the theoretical treatment of Tonks-Girardeau gases is simplified by the Fermi-Bose mapping theorem [2], which allows local density and correlation functions of strongly interacting Bose gases to be related directly to those of free fermions.

Preliminary results are presented, outlining the centre of mass motion of the impurity atoms and density profiles for both components. Results show good qualitative agreement with experimental data, though the large density fluctuations seen in the experiment have so far not been observed 'upstream'. Figure 1 shows density profiles for the impurity atoms (red) and the in-trap component (blue) before and after acceleration by gravity. Current work and planned refinements to the simulation are also presented.

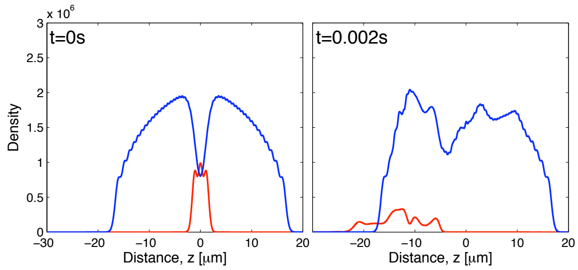

Figure 1: (left) Initial density profiles for impurity atoms (red) and in-trap component (blue) for a sample of 50 Rb atoms.
(right) Density profiles after 0.002s. Impurity atoms have been accelerated downwards by gravity, experiencing significant dissipation due to strong interactions with the trapped cloud (trap frequency $\omega_z = 2\pi \times 39$ Hz).

Keywords: TONKS, TONKS-GIRARDEAU, IMPURITY, QUANTUM TRANSPORT

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An Apparatus for Bose-Einstein Condensates in Novel Traps by Time Averaged Adiabatic Potentials

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Abstract

Time Averaged Adiabatic Potentials (TAAP) offer an unprecedented potential for the manipulation of ultracold atoms and Bose-Einstein Condensates. Various trapping geometries can be formed, from multiple well structures, to ring potentials, and even pancake traps. The TAAP [1, 2] is produced by combining static and oscillating magnetic fields with RF-dressing fields. For example, we can form an atom guiding ring if we start off with a quadrupole field modulated by a homogeneous field and then, applying a modulated RF-field such that it is resonant with the atoms on a ring. This yields an extremely flexible and tightly-confining trapping geometry. The radial confinement can be in the kHz range, whereas the diameter of the ring can be tuned from about 30 micrometers to a few centimetres: ideal conditions for a guided matter-waveSagnacinterferometer.

Here, we present the Cretan BEC machine, which has been designed for the exploration of TAAP traps. In our experiment, atoms are loaded into a TOP trap [3] via a double magneto-optical trap system. A 2D-MOT produces an atomic beam, with a flux of 10^9 atoms/s, which is directed into an ultra-high vacuum science chamber where the atoms are collected into a standard MOT. After loading, the MOT is compressed, and the atoms transferred into the TOP trap. Thus, approximately 10^9 atoms at around 500 micro-Kelvin are trapped ready for further evaporative cooling, and manipulation by the TAAP.

We will detail some of the technical challenges, such as the RF generation, and their solution.

Keywords: atom interferometry, Bose-Einstein condensation, adiabatic potentials

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Mobile accelerometers based on atom interferometry for high-precision measurements of local gravity

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Abstract

Since 1991, matter wave interferometry has been used in many laboratories for a variety of fundamental physics experiments, e.g. measurement of the fine-structure and gravity constants. However, due to the complexity of these experiments, they were confined to laboratory environments. Only in recent years efforts have been undertaken to develop mobile atom interferometers. These new sensors open up the possibility to perform on-site high-precision measurements of rotations, gravity gradients as well as absolute accelerations.

GAIN (Gravimetric Atom Interferometer) is a mobile and robust gravimeter that is being developed within the framework of the EuroQUASAR/IQS programme. It is based on interfering ensembles of laser cooled ^{87}Rb atoms in a one meter high atomic fountain configuration. With a targeted accuracy of a few parts in 10^{10} for the measurement of local gravity g this instrument will offer about an order of magnitude improvement in performance over the best currently available absolute gravimeters. Together with the capability to perform measurements directly at sites of geological interest, this opens up the possibility for a number of interesting applications: As this technology will significantly improve the precision of gravity measurements in fields such as geodesy, geophysics or seismology, our project profits from collaborations with EuroQUASAR/IQS partners in geophysical communities.

We introduce the working principle of our interferometer and give an outline of the subsystems needed for a mobile setup. Characterisations of the most vital subsystems are given, including a rack-mounted cooling and Raman laser system, a very low-noise optical Raman laser phase lock and a highly adaptable yet mobile main vacuum chamber setup. Latest measurements of local gravity are presented and the next steps necessary to achieve full accuracy are discussed.

Secondly, we present the Space Atom Interferometry (SAI) project that investigates both experimentally and theoretically the different aspects of placing atom interferometers in space: the equipment needs, the resulting device sensitivities, and what physics might be done using such systems. For these purposes, the project brings together European institutions to share their mutual expertise and to collaborate on the construction of an atom interferometer testbed geared towards future applications in space. We give an overview of the sensors ultra-compact design and report on the status of its first completed subsystems. Finally, applications of the testbed apparatus that most closely approximate space environment conditions on earth are discussed. The SAI project is financed by ESA (contract 20578/07/NL/VJ). http://www.physik.hu-berlin.de/qom

Keywords: Atom Interferometry, High-Precision Measurements, Gravimetry, Accelerometer, Cold Atoms, Geodesy

High precision cold atom gyroscope

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Abstract

Due to its high potential, matter wave interferometry has been investigated as a tool for high precision inertial measurements for years [1]. The research topic of the CASI project (Cold Atom Sagnac Interferometer) is a gyroscope using laser cooled Rubidium atoms and aiming for a sensitivity of a few 10^{-9} rad/s/Hz$^{1/2}$ for 10^{8} atoms per shot [2]. The atomic ensemble is launched in a pulsed mode onto a flat parabola with a forward drift velocity of 2, 79 m/s [3] leading to an interrogation time of over 50 ms. Via coherent beamsplitting using Raman transitions, the atomic trajectories forming the interferometer paths can enclose an area of several mm^2. In this talk we discuss the influence of the main noise sources which limit the sensitivity of our quantum sensor. Particularly, contributions affecting the beam splitting process as well as the detection will be considered. Furthermore, the lastest interferometry measurements will be presented. This work is supported by the DFG, QUEST, and IQS.

Keywords: ATOM INTERFEROMETRY, INERTIAL SENSOR, METROLOGY, GYROSCOPE

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Spatial evolution of the phase and spin-echo rephasing in a two-component BEC

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Abstract

Knowledge of phase dynamics in matter waves is the critical factor in studying BEC coherence for potential applications of BEC interferometers. We observe interesting spatial evolution of the relative phase in an elongated condensate [1]. Our two-component system is comprised of the $|F = 1, m_F = -1\rangle$ and $|F = 2, m_F = 1\rangle$ hyperfine ground states of ^{87}Rb, magnetically trapped on an atom chip and interrogated via two-photon Ramsey interferometry. The phase evolution is strongly influenced by intra- and inter-species nonlinear interactions.

The first $\pi/2$ pulse prepares the system in a non-equilibrium state and the subsequent nonlinear evolution of each component leads to the relative phase becoming inhomogeneous along the axial coordinate, varying by 2π across the condensate after 95 ms of evolution. The second $\pi/2$ pulse locally converts spatial variations of the phase into the spatial variations (fringes) of the atomic density of each state which change with the evolution time (Fig. 1). The spatial dependence of the relative phase manifests in inhomogeneous dephasing of the condensate wavefunction along the axial dimension and, as a result, we observe relatively fast decay of Ramsey interference fringes (decay time $\sim$ 70 ms). Inhomogeneity of the relative phase of the condensate wavefunction is the dominant mechanism for the loss of the Ramsey fringes, rather than decoherence due to coupling to the environment or quantum phase diffusion.

Reversing of the mean-field-induced dephasing is achieved using the application of a spin-echo pulse sequence at appropriate times. We observe the recovery of the interference contrast and extended coherence time.

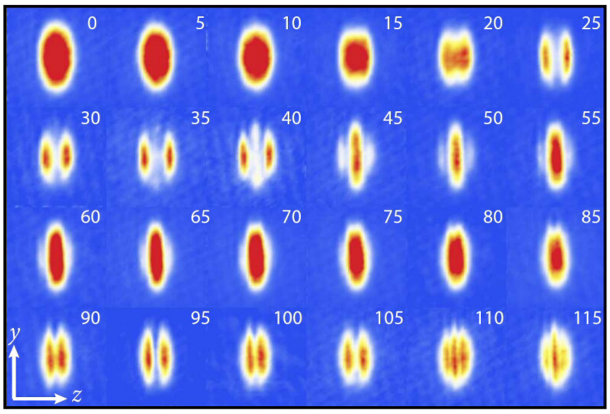

Fig. 1: Single shot absorption images of the condensate in the state $|F = 2, m_F = +1 >$ taken after 20 ms of free fall and expansion with varying Ramsey interferometry time (in ms).

Keywords: BOSE-EINSTEIN CONDENSATE, MATTER-WAVE INTERFERENCE, DECOHERENCE

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Surface Quantum Optics: from Casimir-Polder forces to tailored optical near-fields

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Abstract

Surface Quantum Optics is a new field of physics which combines ultracold atoms with solid surfaces in order to generate surface nanotraps for cold atoms and build hybrid atom - solid state systems [1]. Along this way physical effects have to be faced like Casimir Polder forces which are typically strongly attractive. Such forces are one of the few examples where the vacuum energy leads to measurable effects and can be used for tests of QED. The precise knowledge of Casimir forces is also important for the development of nanomechanical systems. Therefore, measurements of Casimir-like forces have gained enormous interest in the last few years. Our surface quantum optics group in Tbingen recently directly measured the Casimir-Polder force in the so-called transition regime.[2] This regime is of special interest because here deviations from the power law formulas which are valid in the limiting cases of short and large distances are expected. The measurement was performed by balancing the unknown surface potential with the known dipole potential of an evanescent wave. Such potentials are steep enough to compensate Casimir forces at distances down to hundred nanometers from the surface. Even smaller distances could be reached when the optical near-field is enhanced by surface plasmon resonances. These are collective excitations of electrons in a thin metal film on the surface. By structuring the metal film the optical near field can also be shaped in the transverse direction above the surface. This will be one of our next steps. This technique will allow us to generate optical nanopotentials for cold atoms with the prospect to build nano-traps and elements for nano atom-optics on surfaces.

Keywords: cold atoms, surfaces, QED, Casimir force, evanescent wave

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Entanglement and Distinguishability of Quantum States

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Abstract

Entanglement is an algebraic property of quantum states. Its physical interpretation is typically related to non-locality. In our talk we will show that entanglement is physically related also with the concept of distinguishability of quantum states. Lets consider two systems differing by a unitary transformation. Can we decide if the two corresponding states are different with a finite number of measurements? This would be possible only if the difference between the state probabilities is smaller than the fluctuations of the results of the measurements [1]. It is therefore possible to define a statistical distance which is the number of distinguishable states along a certain path in the Hilbert space.

We demonstrate that quantum mechanics put an upper bound on the minimal statistical distance among two classically correlated states of N q-bits. However, if the q-bits are entangled, the statistical distance can be reduced up to a factor $\sqrt{N}$. In other words, entangled states can evolve faster under unitary transformations than classical states. This has important implications in the theory of quantum Zeno dynamics [2] as well as in interferometry and, quite generally, in the theory of a parameter estimation [3]. In particular, we will show that entanglement is a necessary resource to overcome the shot noise limit and saturate the Heisenberg limit, the highest sensitivity allowed by quantum mechanics.

Keywords: Entanglement, quantum interferometry, quantum Zeno dynamics

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Precision Measurements with Ultracold Earth Alkaline Atoms

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Abstract

Earth alkaline atoms have unique properties that make them well suited for precision experiments like optical clocks. Due to their non-degenerate ground state, the associated simpler molecule structure of alkaline earth dimers allows for more accurate investigations of collisions [4, 1]. Moreover, the vanishing magnetic moment in the ground and excited state will allow for novel applications in atom interferometry not hampered by phase shifts due to magnetic fields.

In a lattice clock with ^{88}Sr we have determined the influence of collisions on the $^1S_0$ - $^3P_0$ clock transition. Using ^{88}Sr atoms in a magic wavelength one dimensional optical lattice we were able to quantify the effects of collisions on the $^1S_0$-$^3P_0$ clock transition [2]. These effects are a collisional shift, dephasing collisions, and inelastic collisions between atoms in the upper and lower clock state, and atoms in the upper clock state only. Based on these results we determine the operation parameters at which a 1D-lattice clock with ^{88}Sr shows no degradation due to collisions on the relative accuracy level of 10^{-16}.

Currently we investigate the fermionic isotope ^{87}Sr for its use in an optical lattice clock, where systematic uncertainties close to 10^{-16} have been achieved [3]. Comparing two an interleaved stabilizations under similar conditions, we have obtained a fractional frequency instability of 10^{-16} at 1500 s averaging time.

For the most abundant calcium isotope, ^{40}Ca a positive ground state s-wave scattering length of a few hundred atomic units was estimated from photoassociation measurements and from molecular spectroscopy [4]. This has allowed the successful Bose-Einstein-condensation of ^{40}Ca by forced evaporative cooling in a crossed optical dipole trap [5]. Special care was necessary to optimize the loading of the dipole trap from a two stage MOT [6] and to avoid excessive three body loss connected to the large ground state s-wave scattering length (approximately 350 a_0 - 700 a_0) of ^{40}Ca. We will present the optimized route to BEC and discuss future applications.

This work was supported by the Centre of Quantum Engineering and Space-Time Research (QUEST), the European Community's ERA-NET-Plus Programme, and by the ESA and DLR in the project Space Optical Clocks.

Keywords: optical clocks, BEC, ultracold collisions

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Atom chip based generation of entanglement for quantum metrology

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Abstract

Entanglement-based technologies, such as quantum information processing, quantum simulations, and quantum metrology, have the potential to revolutionize our way of computing and measuring, and help clarify the puzzling concept of entanglement itself. Ultracold atoms on atom chips are attractive for their implementation, as they provide control over quantum systems in compact, robust, and scalable setups.

In this talk we report experiments where we generate multi-particle entanglement on an atom chip by controlling elastic collisional interactions with a state-dependent potential [1, 2]. We employ this technique to generate spin-squeezed states of a two-component Bose-Einstein condensate that are a useful resource for interferometry beyond the standard quantum limit. The observed -3.7 ± 0.4 dB reduction in spin noise combined with the spin coherence imply four-partite entanglement between the condensate atoms and could be used to improve an interferometric measurement by -2.5 ± 0.6 dB over the standard quantum limit. Our data show good agreement with a dynamical multi-mode simulation [3] and allow us to reconstruct the Wigner function of the spin-squeezed condensate. The techniques demonstrated here could be directly applied in chip-based atomic clocks which are currently being set up.

Keywords: ultracold atoms, atom chips, entanglement, spin squeezing, quantum metrology

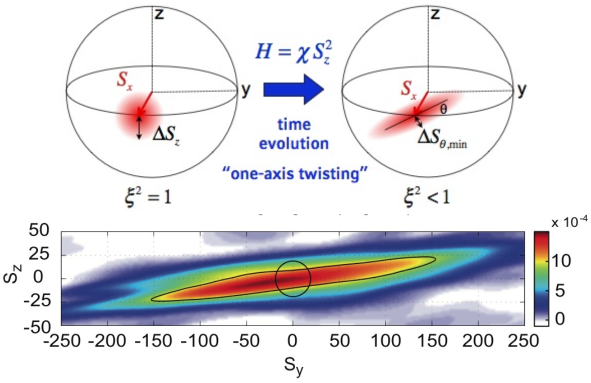

Figure 1: Spin-squeezing in a Bose-Einstein condensate on an atom chip. Upper graph: spin-squeezing through time evolution with the nonlinear one-axis twisting Hamiltonian. Lower panel: Wigner function of the spin-squeezed state reconstructed from our experimental data. The squeezed and anti-squeezed quadratures are clearly visible by comparing with the uncertainty circle of a coherent spin state.

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Towards the Southampton molecule interferometer

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Abstract

Matter wave interference experiments with large molecules are of interest to address fundamental physics related to the quantumness of macroscopic particles - as well as for applications like molecule metrology as demonstrated by the Vienna experiments. We will report on the progress of setting up our vertical molecule Talbot-Lau interferometer at Southampton. This three material grating interferometer will enable interference and metrology experiments of molecules of up to 10,000 amu (atomic mass units), which is an important intermediate step towards very massive particle interferences to attack the fundamental questions. That mass range is especially important for metrology experiments with organic molecules. While some analytic methods are already demonstrated, as the measurement of molecule's polarizability and dipole moment [1], other proposals are still waiting for their experimental realizations [2]. On top of that interferometric molecular beam sorting was proposed and demonstrated for two fullerne species [3] and needs to be demonstrated for organic molecules. Furthermore molecular quantum interference lithography as a new tool as a bottom up nanofabrication approach seems to be possible [4]. These applications of precise molecule interferometric deflectometry have quite some impact for commercial applications for instance as a complement to mass spectrometry.

We choose a vertical orientation to control the effects of Earth's gravity and rotation on molecule interference. This is already important for molecules at velocities of below 50 m/s and shall become essential as more massive particles needs to be slower for a given de Broglie wavelength λ. We will describe our beam setup with the new molecular beam velocity selector which was designed and tested at Southampton and performs a selection of $< 6\%$ (FWHM). We will also report on the novel flexible/adjustable three grating interferometer system. The latter enables to measure the diffraction pattern fine structure at some Talbot lengths (d^2/λ) after the diffraction grating of period d. This fine structure information will help to increase the precision of measurable quantities by molecule interferometry.

Planned studies include the mapping of molecule distribution and a reconstruction of the Wigner function of diffracted molecules as well as the manipulation like deceleration and cooling of molecules by light and van der Waals/Casimir-Polder interactions of the molecules with the diffraction gratings. Here we work together with the Southampton nanofabrication centre to manufacture various grating structures and designs from different materials.

Keywords: molecule interferometry, molecule metrology, Talbot-Lau interferometer

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Sub-Poissonian atom number fluctuations by three-body loss in mesoscopic ensembles

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Abstract

The study and control of particle number fluctuations has revealed a rich variety of intriguing quantum phenomena in ultracold quantum gases, such as atom (anti)bunching effects, manybody correlations, squeezing and entanglement. In these experiments the random loss of atoms is generally considered deleterious. We show, however, that three-body loss of trapped atoms naturally leads to sub-Poissonian atom number fluctuations, analogous to intensity squeezing in optics [1].

We prepare hundreds of dense ultracold ensembles in a two-dimensional array of magnetic microtraps on an atom chip, which subsequently undergo rapid threebody decay [2]. The shot-to-shot fluctuations of the number of atoms per trap are subPoissonian, for ensembles comprising 50–300 atoms. The effects of residual imaging noise are greatly reduced through the application of spatial correlation analysis which exploits the lattice geometry and provides a way to isolate the atom number fluctuations. Our results are in very good agreement with a simple model which takes into account the fluctuations. This shows that threebody loss processes can be used for the preparation of small and well-defined numbers of atoms in each trap.

We expect this to be an ideal system for the study of collective excitations produced via laser excited Rydberg states for quantum information processing with neutral atoms [3]. Such mesoscopic ensembles would benefit from a $\sqrt{N}$ collective enhancement of the Rabi frequency over single atoms for fast quantum operations, and have desirable properties for the generation of many-particle entangled states or as a resource for quantum metrology.

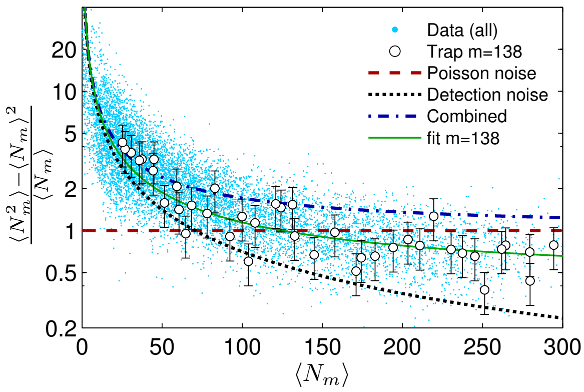

Figure 1: Atom number fluctuations measured for each of 245 individual lattice sites during three body decay. Open circles indicate the measurements for a selected trap.

Keywords: MESOSCOPIC, THREE-BODY, SQUEEZING, MICROTRAP, ATOM CHIP, ENSEMBLES, FLUCTUATIONS

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Controlling spin dynamics in a one-dimensional quantum gas

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Abstract

Reducing the dimensionality of a system has dramatic consequences and leads to remarkable new physics. In this regard, quantum gases offer unique opportunities to address important open questions in quantum many-body physics, by allowing full control over all relevant parameters.

We create coherent superpositions of both spin and motional degrees of freedom and probe spin dynamics of a one-dimensional (1D) Bose gas of ^{87}Rb on an atom chip. We observe interaction-driven dynamics of one spin component by mean field interaction with another component, directly related to the effective 1D interaction strength. We demonstrate experimental control over the 1D interaction strengths through state-selective radio-frequency dressing [1]. The dynamics are altered by tuning the trapping potential in a state-dependent way as a means to modify the inter-and intra state interactions. This enables, for instance, access to the point of spin-independent interactions where exact quantum many-body solutions are available [2, 3] and to the point where spin dynamics are frozen.

Keywords: many-body, spin, interactions, one-dimension, Bose-gas, dynamics, dressed potentials

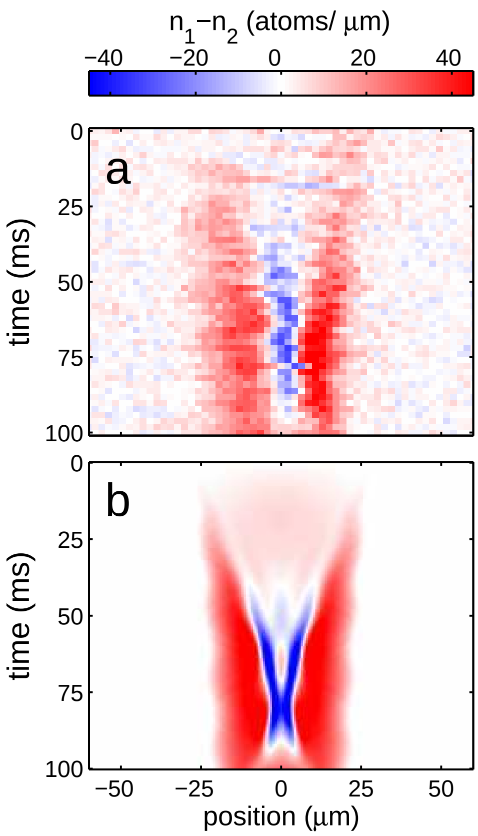

Figure 1: (a) Observed evolution of spin polarization in one dimension. (b) Corresponding numerical Gross-Pitaevskii simulation. Clearly, the spin polarization shows rich dynamics, well captured by the simulation. The total density (not shown) does not evolve in time.

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Emerging beam resonances in atom diffraction from a reflection grating

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Abstract

It is a general phenomenon in wave optics that diffraction by a periodic surface shows peculiar intensity variations in the outgoing beams when conditions are such that a diffracted beam just emerges parallel to the surface. This was first observed by Wood in 1902 and is known as Wood anomalies in light optics [1]. Rayleigh in 1907 first traced back Wood anomalies to grazing emergence of a diffracted beam [2]. Later on Wood anomalies were categorized into two cases, one (sharp anomalies) related exclusively to the emergence of a diffracted beam (Rayleigh-Wood anomaly) and the other (broad anomalies) to resonance effects [3, 4].

In atom optics a behavior in analogy to the resonance type anomaly has been investigated for a long time under the name of selective adsorption [5], which was first observed by Estermann and Stern in 1930 in the scattering of helium atoms from crystal surfaces [6]. It is accounted for by a bound state of the atom-surface interaction potential. On the other hand, Rayleigh-Wood anomalies which, in atom diffraction, are referred to as *emerging beam resonances* have not been observed in atom surface scattering experiments, although they have been predicted by theory [8, 9].

Here we report the first observation of emerging beam resonances in atom optics. Helium atom beams are diffracted from a plane ruled grating at near grazing incidence. By varying the incidence angle we observe the resonances at the Rayleigh incidence angles in two ways; (i) the total reflectivity of the grating increases steeply, (ii) the intensity curves of the diffracted beams and the specular beam exhibit abrupt changes of their slopes. We adopt the multiple scattering approach of Rayleigh [2] and Fano [3] to explain basic features of our observations. Our results complete the analogy between photon optics (*Rayleigh-Wood anomaly* and *resonance type Wood anomaly*) on the one hand and atom optics (*emerging beam resonance* and *selective adsorption*) on the other hand.

Keywords: atom optics, Wood anomalies, emerging beam resonance, grating diffraction

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Quantum reflection of helium atom beams from solid surfaces

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Abstract

We have identified quantum reflection as a mechanism of coherent reflection from microscopically rough surfaces like, e.g., glass [1]. In quantum reflection a wave packet is reflected at the attractive branch of the atom-surface potential. In contrast to classical mechanics there is no classical turning point resulting from a repulsive potential branch. As quantum reflection takes place tens of nanometers above the surface where the equi-potential surfaces are flat, the coherent reflection probability is hardly diminished by the roughness of the actual surface.

In a first experiment we have observed high-resolution diffraction patterns of a thermal-energy helium atom beam reflected from a microstructured surface grating at near grazing incidence. The grating consists of 10-μm-wide Cr strips patterned on a quartz substrate and has a periodicity of 20 μm. Fully resolved diffraction peaks up to the seventh order have been observed at grazing angles up to 20 mrad. With changes in de Broglie wavelength or grazing angle the relative diffraction intensities show significant variations which shed light on the nature of the atom-surface interaction potential. The observations are explained in terms of quantum reflection at the long-range attractive Casimir-van der Waals potential [1].

In another experiment we have demonstrated 1-dimensional focusing of a thermal helium atom beam by quantum reflection from a cylindrical concave quartz mirror at near grazing incidence. Three effects have been observed to contribute to the finite focal width; (i) the finite size of the atom beam source; (ii) diffraction at the beam-collimating aperture; and (iii) spherical aberration. The smallest width of the focus that has been achieved is 1.8 μm, essentially limited by spherical aberration. We propose to apply near-grazing reflection from two concave elliptical mirrors in a Kirkpatrick-Baez arrangement for 2-dimensional focusing of a helium atom beam, paving the way for a helium atom microprobe with a lateral resolution on the order of 100 nm [2].

Furthermore, we have investigated the transition from quantum to classical reflection with thermal helium atom beams scattered off various microscopically-rough flat surfaces at near grazing incidence. For a sufficiently small normal component k_z of the incident wave-vector of the atom the reflection probability is found to be a function of k_z only, and is explained by quantum-reflection as described above. For larger values of k_z, however, the overall reflection probability is found to also depend on the parallel component k_x of the wave-vector. The k_x dependence for this, presumably, classical reflection from the repulsive branch of the potential is material dependent and depends also on the actual surface roughness as it is probed under grazing incidence conditions.

Keywords: quantum reflection, atom optics, diffraction, grating

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