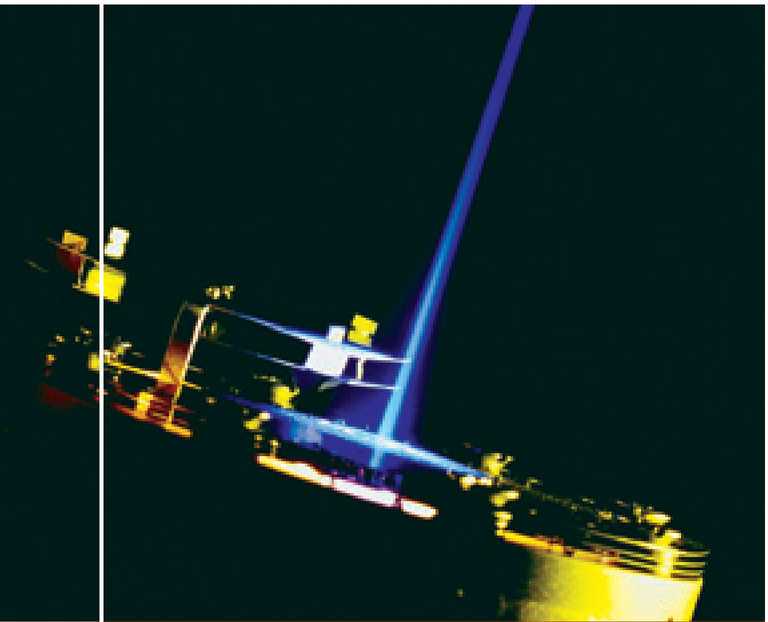
Atom optics

Coherent atom sources and applications

Besides traditional light optics, matter-wave optics gains more and more importance. By means of appropriate optical elements (lenses, mirrors, etc.), researchers in this field influence and control the motion of particles, ranging from electrons, neutrons, neutral atoms, ions up to macroscopic bio-molecules. A well known example are



electron beams which are commonly used in electron microscopes to image sub-nanoscale structures, or in electron beam lithography to modify surfaces on an atomic scale. The concepts of light optics were recently transferred also to atom optics (see e.g. ref. 1). Mechanical gratings, conservative potentials generated by light, magnetic or electric fields are used to realize optical elements like lenses, mirrors, beam splitters, waveguides and atomic traps (atom resonators). The role of light and matter gets interchanged in atom optics. Light is used to manipulate matter, whereas in light optics, matter is used to manipulate light. Both photons and atoms, show particle- and wave-like properties. For an atom the wavelength is given by the de Broglie wavelength (λ_{dB}=h/(m v), where h, m and v are Planck's constant, the particle mass and the velocity) and for a photon the momentum is given by p=h/λ, where λ is the light wave length.

SUMMARY

In the past few years, atom optics has rapidly gained importance and belongs nowadays to the central topics of modern optics. Atom optics combines techniques, which allow to manipulate the trajectories of atoms. Hereby, potentials generated by light, magnetic or electric fields, provide optical elements like lenses, mirrors and beam splitters. In many cases, techniques known from classical light optics can be directly adopted to atom optics. Moreover, further properties of atoms including internal structure, mass and interaction between atoms lead to new optical elements that have no counterpart in light optics.

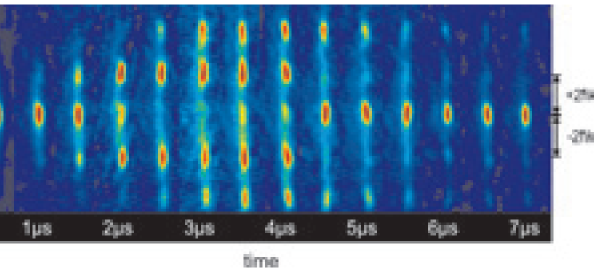
Dissipative elements allow slowing down, cooling and trapping of atoms. Advances in cooling techniques enable researchers to achieve Bose-Einstein condensation in trapped atomic gases. The phase transition from a thermal gas of identical bosonic atoms to a Bose-Einstein condensate occurs at very low temperatures ($T<1\mu K$) as soon as the extension of the quantum mechanical wave packet describing an individual atom, exceeds the interatomic separation. The gas becomes a macroscopic quantum object, which is characterized by a single wave function. A very similar behavior can be observed at the laser threshold in a light laser. According to a laser beam, a beam of coherent atoms coupled out of a Bose-Einstein condensate is called an atom laser beam.

Bose-Einstein condensates represent ideal and very flexible model systems which are used to study very diverse physical problems. Atomic quantum gases are well accessible since they can be observed by CCD-cameras besides being handled and controlled using atom optical elements. Interactions between the atoms lead to a Kerr-nonlinearity like it is known from nonlinear optics. Thus, e. g. four wave mixing and matter wave amplification can be observed in these gases. Whilst this article stresses analogies between light optics and atom optics, recent research on Bose-Einstein condensates goes beyond the scope of optics.
Measurements with condensates in periodic three-dimensional optical lattices are used to address solid state phenomena and problems. Recent studies of high-temperature superconductivity on the basis of data obtained from degenerated fermionic atomic quantum gases show that atom optics has developed to very interdisciplinary field of research.

1. Introduction

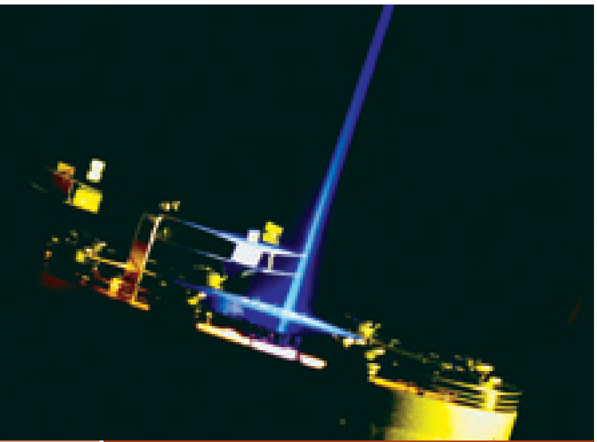
The field “atom optics” started in the early 1920s, when Stern and Gerlach showed that inhomogeneous magnetic fields exert a force on atomic magnetic moments. Already in 1927 Stern could demonstrate the reflection and diffraction of atoms from a metal and a crystal. In 1933, Frisch showed that an atomic beam can be deflected by light pressure. The first demonstration of a magnetic lens succeeded in 1951 by Friedburg and Paul. It took until 1978 when Bjorkholm and coworkers focused for the first time an atomic beam in a near-resonant co-propagating laser beam. Nowadays, atom beams and trapped atom clouds have become workhorses in modern atom optics. New cooling techniques involving light forces and atom evaporation enable researchers to obtain trapped atomic samples, with temperatures extremely close to zero Kelvin. It enables researchers to observe a phase transition to a new state of matter “Bose-Einstein condensate”, which occurs in bosonic gases in this temperature regime. This step which was awarded with a Nobel price in 2001 is comparable to the step from a thermal light source to a coherent laser source, in which a macroscopic number of bosonic photons occupy the same state. It made coherent atom sources and giant matter wave functions accessible for atom optics.

Despite of many common properties, there are lots of fundamental differences between atoms and photons. In contrast to photons, the atoms possess rest mass and have velocities well below the speed of light. These velocities are adjustable through atom optical methods. The quantum statistics of both, photons and atoms is determined by their spin. Photons have integer spin and thus obey the Bose-statistics. Unlike that, atoms (e.g. different isotope or different elements) have either integer or half-integer spin depending on the number of elementary particles of which they are composed, and thus obey either Bose- or Fermi-Dirac-statistics. By choosing fermionic isotopes measurements with degenerate fermionic quantum gases become possible. The internal structure of an atom enables to generate a huge variety of new tools, which are not known from light optics. Moreover the interaction between the atoms causes an additional nonlinear term in the wave equation, which is formally equivalent to the Kerr non-linearity in a non-linear material. Like in light optics, four wave mixing, solitons as well as up- and down conversion have been observed. Very exciting are experiments which combine Bose-Einstein condensates or degenerate Fermi gases with periodic optical lattices. Since in this model system both the periodic potential and the interaction of the gas can be easily adjusted, it is ideally suited to address basic solid state problems.



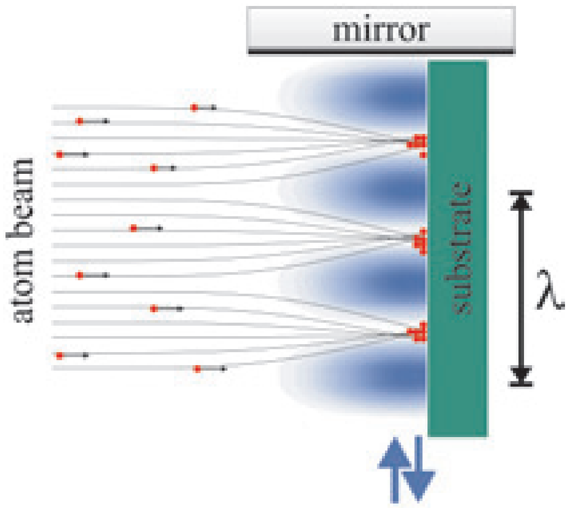
01

Diffraction of a rubidium matter wave in a one-dimensional optical lattice depending on the interaction time between lattice and matter wave.



02

Thermal beam of chromium atoms illuminated by resonant laser light above a high temperature effusion cell.



03

Principle of atom lithography: A standing blue detuned light wave created by a back reflected laser beam with the wavelength λ, focuses atoms of an atom beam onto lines on the substrate. The generated atom lines are separated by λ/2.

E.g. **(01)** depicts diffraction of a matter wave in a one-dimensional optical lattice. In the following we want to stress analogies and differences between light and atom optics and discuss exemplarily a few recent experiments of our group.

2. Atom lithography

The resolution of a far-field optical instrument is typically limited by refraction to half the wavelength of the applied light. Since the de Broglie wavelength of a thermal atom beam is typically only a few picometers and is thus comparable to x-ray radiation, one should in principle achieve resolutions well below the resolution limit of light optics. Lenses in atom lithography can be realized for instance by using the interaction of near resonant laser light and the light induced dipole moment of an atom. Depending on the laser frequency with respect to the atomic transition (detuning of the laser), the atoms are forced into high or low intensity regions of the light field. Many light field configurations result in approximately harmonic optical potentials that are ideally suited for atomic lenses. For instance, a standing optical light wave in front of a surface as depicted in **(03)** is a perfectly spaced array of cylinder lenses, which can be used to nano-structure the surface over a large area. In the experiment depicted in **(03)**, a collimated chromium atom beam of a thermal source **(02)** is directed onto a surface. The atoms are focused into the nodes of the blue detuned standing wave. If the substrate is placed in the focal point of the lenses, the atoms are deposited in lines on the surface with a line spacing of λ/2. We were able to structure the surface with a structure width of 50 nm in one and two **(04)** dimensions. The atomic lenses are extremely flexible and can be modified during the deposition. This method is especially applicable to periodic patterns. Non-periodic structures require more complex light masks and are harder to produce, but have been demonstrated by holographically generated light fields. Multilayer light masks which correspond to lens systems promise optimized atomic images.

In this respect, atom lithography is an example which shows a close analogy to the classical ray optics. However, light lenses for atoms possess unique properties, which lead to specific strengths of atom lithography in nanofabrication. Since the lenses rely on the resonant interaction between light field and the atoms, the lens is extremely element and even isotope selective. It becomes possible to produce different structures of different elements simultaneously. This property allows growing of materials that are nano-structured in three dimensions **(05)**. Hereby at least two materials – a light field sensitive dopant and a non-sensitive host material – are simultaneously deposited. During the deposition process, the light mask will only focus the dopant and leave the host material unaffected, which will lead to a homogenous growth of the host material. By moving or rotating the surface, nano-tailored matter can be produced which has been discussed in the context of photonic crystals. The interplay of the internal structure of the atoms and polarization gradients in the light field is another feature that can be used to modify the properties of the lenses and reduce the structure spacing below λ/2. A third aspect is the dissipative force arising from absorption and emission of photons. Atomic lenses cannot only focus atoms, they can at the same time cool their motional degree of freedom. A more detailed overview on the activities can be found in ref. 2.

3. Coherent atom sources

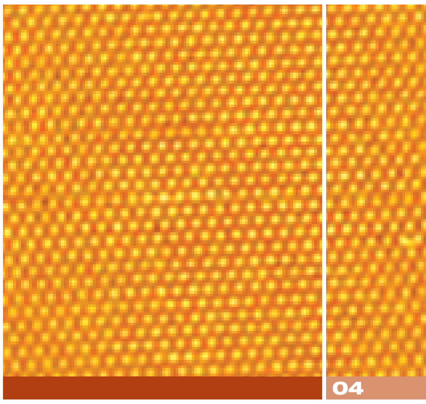
The experiments discussed up to here are carried out using thermal atomic beams. In conventional optics, the step from a light bulb to an optical laser in the 1960s enabled a huge technological progress and a variety of new, fascinating scientific experiments including most of the atom optics experiments. An equally important step in atom optics is the step from a thermal atom source to a coherent atom source. While an optical laser emits a beam of coherent electromagnetic waves, the output of an atom laser is a coherent, bright beam of matter waves.

The principle of such a coherent atom source is based on a postulation of Albert Einstein in 1925, who seized a suggestion of Satyendra Bose on the quantum statistics for identical particles with an integer spin quantum number (bosons). He stated that in an ideal gas bosons can macroscopically occupy the ground state, even if the thermal energy exceeds the level spacing. This occurs, if the thermal de Broglie wavelength becomes comparable to the mean particle separation, more precisely the phase space density rises above 2.6. The Bose-Einstein condensation (BEC) is a phase-transition which relies on pure quantum statistical effects and needs no particle interaction. For fermions (particles with half integer spin quantum numbers) a gradually transition from a classical gas to a degenerate Fermi gas can be observed if the above condition is fulfilled. The critical temperature depends on the density and particle mass. Thus, quantum effects for electrons, for phonons in solids or for liquid helium become significant at relatively high temperatures (in the order of 10^4 K, 100 K and 1 K, respectively). In bosonic atomic gases the phase transition can only be achieved in dilute systems ($n \sim 10^{13}$ atoms/cm^3) at temperatures below 1 µK (see e.g. ref. 3). Thus, it took 70 years until the required cooling methods and experimental techniques could be developed to realize a condensate in trapped atomic gas. However, the exciting point was not only the technical achievement of a theoretically predicted new state.

For the first time researchers had the unique opportunity to explore the nature of a well observable macroscopic quantum object with a size of up to 0.5 mm. Moreover, thanks to the low density, interactions are weak and the condensates can be well treated theoretically, which made the interplay between theory and experiment extremely fruitful. Therefore, already six years later (2001) Eric Cornell, Wolfgang Ketterle and Carl Wieman have been awarded the Noble Prize in physics “for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensate”.

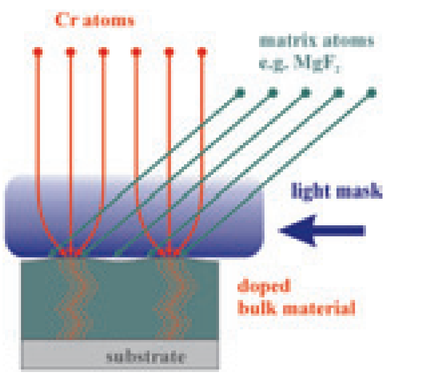
Meanwhile condensates have been created in gases of nine different atomic elements. Due to the very different internal structures and collisional properties of the particles, the cooling techniques must be carefully designed for each atomic species. In our laboratory we recently succeeded to Bose-Einstein condense atomic chromium. This atomic species is especially interesting due to its high magnetic moment which triggers to novel questions in fundamental research, and also due to its technological relevance in atom lithography. Our experimental setup and an overview of the required and very complex experimental cooling strategy are shown in **(06)** and **(07)** and will be briefly discussed in the following.

To produce a BEC in a gas of chromium atoms, a beam of chromium atoms is generated by a high temperature effusion cell at 1600° C and directed to our science chamber. On their way up, the atoms are slowed down by a counter propagating laser beam in a Zeeman slower. In this way, they can be captured in a modified magneto-optical trap (CLIP trap) in the centre of the science chamber. With our cooling scheme we continuously accumulate 10^8 atoms in a magnetic trap. Another laser cooling sequence (Doppler cooling) is applied after the atoms have been compressed in the magnetic trap. However, due to the light momentum transfer, this laser cooling technique limits the achievable temperature of the cloud to 120 µK. Therefore, the near resonant cooling laser light is turned off and the trapped cloud is further cooled by forced radiofrequency (rf) induced evaporation in the magnetic trap. This technique is comparable to evaporation on a macroscopic scale. While hot atoms are removed from the trap, the temperature of the cloud decreases due to rethermalising elastic collisions of the remaining atoms. In a harmonic trapping potential, like it is used in our experiment, the density increases with decreasing temperature. The extraordinarily large magnetic dipole moment of chromium leads to an increasing twobody loss in the form of spin relaxation collisions with increasing spatial density of the cloud. This causes rf evaporation to become inefficient in the magnetic trap and the atoms have to be transferred to an optical dipole trap for the last cooling step. We use a horizontal aligned focused laser beam. To increase the



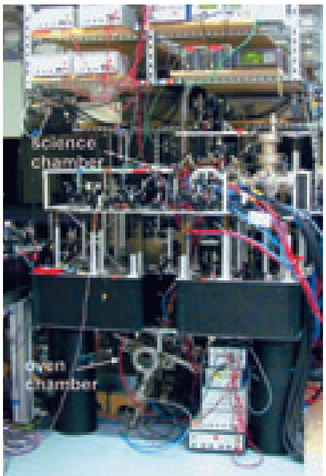
04

Two dimensional chromium nano-dots on a silicon surface. The pattern could be created using three interfering laser beams. The dots have a structure width of 120 nm and are separated by 2λ/3=284.



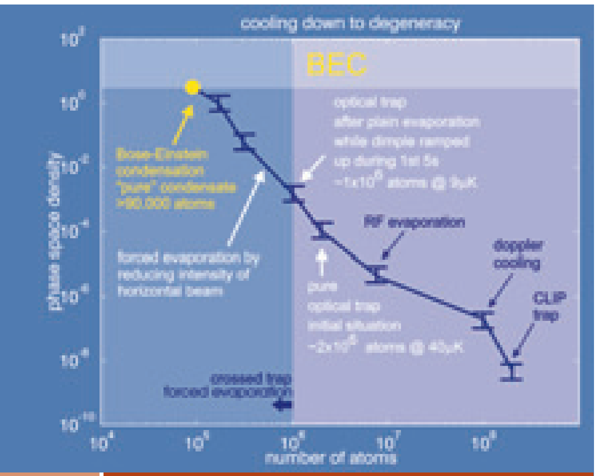
05

Structured doping: A light mask sensitive dopant (Cr atoms) and a light mask insensitive matrix material (MgF_2) are simultaneously deposited on a substrate. While the light mask focuses the dopant atoms, the matrix atoms are unaffected.



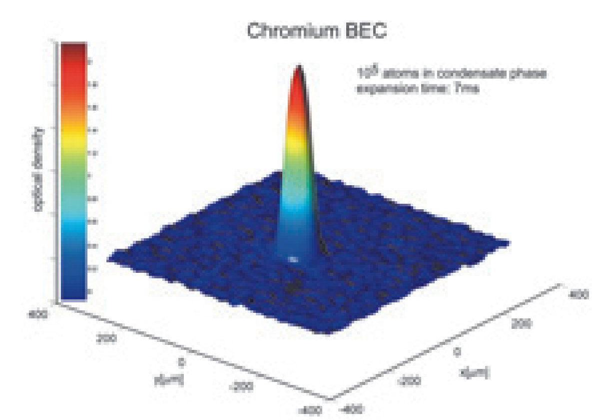
06

Experimental setup.



07

Required cooling steps to obtain a chromium BEC: Shown is the increase in phase space density vs. the trapped atom during the diverse cooling steps, where the phase space density compares the thermal de Broglie wavelength to the interparticle separation. For phase space densities > 1 a BEC forms up in the trapped cloud. During each cooling step atoms are lost, so that the initial atom number of 10^8 atoms drops to 10^5.



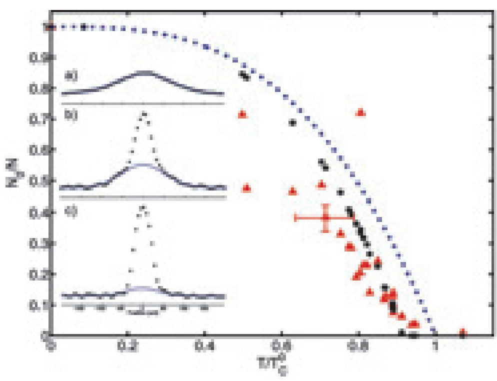
08

False color representation of an absorption image. Shown is the optical density of a chromium condensate consisting of 10^5 atoms after 7 ms of free expansion.

local density and the elastic collision rate during the following evaporative cooling stage, the trapping potential is modified by a second laser beam aligned in the vertical direction. Forced evaporation towards the critical temperature in order to achieve the condensation proceeds now by reducing the intensity of the horizontal beam. The cloud is then detected using a standard absorption imaging technique with a resonant probe beam propagating in the horizontal direction, perpendicular to both trapping beams. A typical image of the condensate containing about 10^5 atoms is shown in **(08)**. **(09)** depicts the typical critical behaviour of the condensate fraction (N_0/N) as the temperature of the sample is lowered.

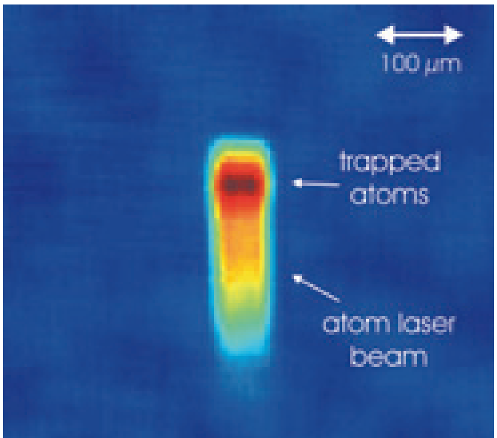
In light optical terminology a BEC represents a resonant cavity highly excited in one mode which is the ground state of the trap. As elastic scattering of atoms is the corresponding process of spontaneous emission in the optical laser, stimulated emission is the scattering process into the ground state of the condensate. As soon as the critical temperature is reached, the atoms scatter predominantly into the ground state, if the sample is further cooled by evaporation. A crucial difference is that atoms cannot be created like photons. The atom number in the ground state can only be increased at the cost of atoms in other states. Phasecoherent matter-wave amplification, as it is known from a laser, could be demonstrated using a BEC of sodium atoms. An input wave generated by Bragg diffraction could be amplified by atoms of the condensate.

Atom traps with BECs were combined with controllable leaks to release a coherent beam of atoms from the trapped condensate. Pulsed atom lasers comparable to q-switched and mode-locked lasers were reported. A chromium atom laser is illustrated in **(10)**. Improving control over the leaks delivered atom laser beams for up to 100 ms from a single Rubidium condensate, until the last atom left the condensate. Up to now the production of a



09

Dependence of the condensate fraction (N_0/N) on the temperature relative to the transition temperature of an ideal gas (T/T_C^0). Besides our measured data (triangles), calculated predictions are indicated by the dashed curve (ideal gas) and the solid circles (including finite atom number and interaction). Inset: Density profiles from absorption images of atom clouds taken after 5 ms of ballistic expansion: (a) thermal cloud at 1.1 µK; (b) two-component (BEC and thermal cloud) distribution at 600 nK, slightly below T_C; (c) nearly pure condensate with 50 000 atoms.



10

False colour representation of a chromium atom laser beam. Atoms leak out of a chromium BEC and form a coherent beam inside an optical wave guide. The atoms are accelerated by the gravity towards the bottom of the image.

condensate needs chronologically ordered cooling steps, which make a continuously pumping of the condensate difficult. Schemes, in which the condensate is prepared in a spatial separated trap and subsequently merged to the "lasing" condensate, are promising.

Again, there are significant differences between a photon and atom laser beam. Due to the very low velocities of the atoms, the propagation of an atom laser beam is

ZUSAMMENFASSUNG

In den vergangen Jahren hat die Atomoptik eine explosionsartige Entwicklung durchlebt und gehört heute zu einem der zentralen Themen in der modernen Optik. Unter dem Stichwort Atomoptik werden Techniken zur Manipulation der Bewegung von Atomen zusammengefasst. Potentiale aus Licht, magnetischen oder elektrischen Feldern dienen in der Atomoptik als optische Elemente, mit denen beispielsweise Linsen, Spiegel oder Strahlteiler realisiert werden können. Wie Photonen in optischen Resonatoren können Atome in Atomfallen für eine gewisse Zeit gespeichert werden. Durch die Realisierung von Bose-Einstein Kondensaten und Atomlasern stehen Quellen kohärenter Materiewellen zur Verfügung. Wechselwirkungen zwischen Atomen ermöglichen nichtlineare optische Elemente. Durch die interne Struktur der Atome und die Wechselwirkung zwischen den Atomen können die Eigenschaften dieser optischen Elemente häufig wesentlich flexibler gestaltet werden, als dies in der klassischen Optik möglich ist.

Dissipative Elemente werden zum Abbremsen von Atomen und zur Kühlung von gespeicherten atomaren Gasen eingesetzt. Der Fortschritt in den Kühltechniken erlaubt es heutzutage, mit atomoptischen Mitteln Gase mit Temperaturen unter 1 nK zu erzeugen. Diese Gase gehören damit zur kältesten Materie im Universum. Quantenmechanisch stellen Atome Wellenpakete dar, deren Ausdehnung mit abnehmender Temperatur wächst. Übersteigt die Ausdehnung identischer, bosonischer Atome den mittleren Abstand zwischen den Atomen in einem gefangenen Gas, so ist es nicht mehr möglich zwischen den Atomen zu unterscheiden. Das Gas muss durch eine gemeinsame Wellenfunktion mit Amplitude und Phase beschrieben werden. Es kommt zu einem Phasenübergang von einem klassischen Gas zu einem sog. Bose-Einstein Kondensat, in dem ein Materiewellenzustand makroskopisch besetzt ist. Einen ähnlichen Übergang kann man an der Laserschwelle eines Lasers beobachten. Analog zum Laser ermöglicht auch hier ein geeigneter Auskoppler aus der Atomfalle einen kohärenten Atomlaserstrahl.

Bose-Einstein Kondensate stellen heute in der Physik ideale, sehr flexible, makroskopische Modellsysteme mit Ausdehnungen bis zu 100µm dar, die zur Untersuchung von unterschiedlichsten physikalischen Fragestellungen genutzt werden. Die Gase sind dabei sehr einfach zugänglich, d.h. sie können sehr gut mit einer CCD-Kamera beobacht und mit atomoptischen Elementen von außen manipuliert und kontrolliert werden. Die Wechselwirkung zwischen den Atomen führt zu einer Kerr-Nichtlinearität, wie sie aus der nichtlinearen Optik bekannt ist und erlaubt es beispielsweise, das Vierwellenmischen und die Materiewellenverstärkung in einem solchen Gas zu beobachten. Obwohl in diesem Artikel besonderes die Analogien zwischen Atomoptik und Lichtoptik hervorgehoben werden sollen, beschränken sich die möglichen Fragestellungen nicht nur auf diesen Bereich. So eignen sich Kondensate in periodischen dreidimensionalen optischen Gittern sehr gut zur Untersuchung von festkörperphysikalischen Problemen. Hochtemperatursupraleitung wird in letzter Zeit an Gasen aus fermionischen Atomen studiert und macht damit die Atomoptik zu einem interdisziplinären Forschungsfeld.

mainly determined by the gravity. The interaction between the atoms will spread the output beam and lead to collisions between two crossed atom beams.

4. Non-linear atom optics

Even though a BEC is a very dilute system, the interaction between the particles cannot be neglected compared to the kinetic energy. Even more, it is the interaction which adds zest to the system. Eric Cornell made the following statement shortly after the first realisation of a condensate in the following way: "…, if the system truly were an ideal gas, there would be little left to study at this point". Because of interparticle interactions in a condensate, the wave equation in the mean field description (Gross-Pitaevskii equation) contains an additional non-linear term, which is equivalent to the Kerr non-linearity in light optics. Thus, it is not surprising that the non-linear optics effects could also be observed in atom optics. However, unlike light optics, where this term arises from the interaction between light and matter, in atom optics the atoms themselves cause these effects.

As we will see in the following, this non-linear term can be easily manipulated over a wide range using external fields. By doing so, the nature of the quantum gas can be modified in a crucial way and different quantum regimes can be investigated.

In most of the quantum gases generated so far, the interaction between the atoms is given by the isotropic van der Waals-interaction and is characterized by the scattering length a, which corresponds to the $\chi^{(3)}$ non-linear coefficient in light optics. Using magnetic field dependent scattering resonances, so called Feshbach resonances, the scattering length can in principle be tuned to any arbitrary value. **(12)** depicts experimentally observed Feshbach resonances depending on the magnetic field in an ultra cold gas of chromium atoms. For example, changing the

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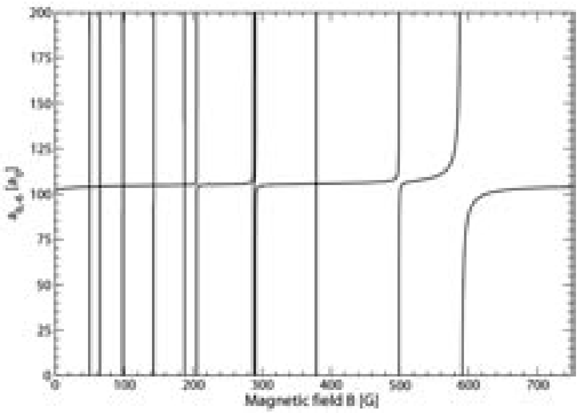
Magnetic wave guide for the realisation of a continuously pumped high-flux atom laser with chromium atoms. Instead of cooling the atoms step by step at the same position, the cooling steps are separated in space.

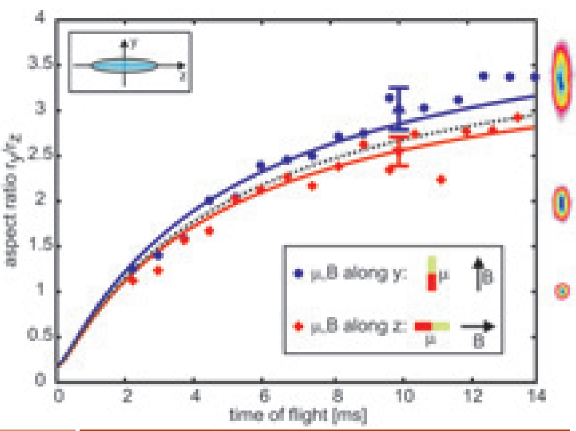


12

Theoretically predicted Feshbach resonances in gas of chromium atoms for magnetic fields ranging from 0 to 750 G. The scattering length a, which describes the van der Waals-interaction diverges in the neighbourhood of the scattering resonance. The scattering length corresponds to the $\chi^{(3)}$ non-linear coefficient in light optics.

scattering length from positive to negative values, i.e. changing the interaction from repulsion to attraction, leads, to a collapse of the condensate wave function. By tuning the scattering length to zero, the BEC behaves like an ideal quantum gas. In recent experiments, a slow sweep of the magnetic field across a resonance resulted in the adiabatic creation of molecules. An inverse sweep transfers the molecules back into atoms. The corresponding process in light optics is up- and down-conversion of light. In a degenerate fermionic quantum gas the quantum static changes during this process. The generated bosonic molecules, themselves can be Bose-Einstein condensed. Applying this technique to a system of fermionic atoms allowed one the investigation of the transition between a molecular BEC and strongly correlated Fermi gas (BCS) and turned out to be an ideal model system to study high temperature super conductivity.

Due to the high magnetic moment of chromium atoms, in a BEC of chromium the strength of the dipole-dipole interaction becomes comparable to the van der Waals-interaction. The two types of interactions differ significantly. While the van der Waals-interaction is isotropic and short-range, the dipole-dipole interaction is anisotropic and long-range. Hence, the properties of these gases are expected to differ significantly from those discussed so far. Because of the anisotropic nature of the interaction, the properties of the quantum gas depend on the direction of the external magnetic field and the shape of the trap. The sign and strength of the average interaction can be changed using rotating external magnetic fields. First experimental results show the dependence of the expansion dynamics of a chromium condensate on the external magnetic field direction **(13)**. The measurement represents not only the first manifestation of dipole-dipole interaction in a degenerate quantum gas but also the first observation



13

Aspect ratios of expanding chromium condensates. The anisotropic interaction induced by the dipole-dipole interaction leads to anisotropic Kerr non-linearity. Thus, depending on the external field direction, the expansion of the chromium condensate is affected.

of magnetostriction in an atomic gas. According to theoretical studies, this interaction should affect the basic properties of a condensate, including e.g. stability, low-lying excitations, roton excitations, Josephson junctions and solitons.

The mass dependence of the non-linear term in the wave equation leads to a third approach, by which the non-linearity of the system can be tuned. According to the effective mass concept in solid state physics, optical lattices are used to obtain an effective negative mass. This approach allowed realising bright solitons with a repulsive interaction.

5. New technological interest

Up to now, we discussed experiments, where an ensemble of atoms is manipulated by classical atom optical tools, which are based mainly on the direct interaction between external fields and the atoms (e. g. atom-light interaction). Applying these techniques, it becomes also possible to individually trap and investigate single atoms. The intensive studies of coherent atom-atom interaction lead to new atom optical tools. For instance, in optical lattices this interaction allows one to purposely control more than 10^5 atoms as a collective. Hereby, a Bose-Einstein condensate is placed inside a shallow optical lattice. As the potential depth of the lattice is increased, the interaction energy of the atoms exceeds the kinetic energy and the atomic cloud undergoes a quantum phase transition from the superfluid to the Mott insulator phase. In the latter phase each lattice site can be occupied by exactly one atom with very small fluctuations in the atom number. Since number fluctuations are drastically reduced, the transition can be regarded analogue to the transition from a classical coherent state to a non-classical Fock state for atoms which find their counterpart in the respective quantum description of light fields. Using this model system, fundamental studies on the quantum phase transitions in lattices could be performed. Atom interferometers based on the phase transition have been proposed.

In our group, we intend to initiate this quantum phase transition close to a surface and deposit equally spaced single atoms on the surface by moving the lattice towards the surface. The scheme is depicted in **(14)**.

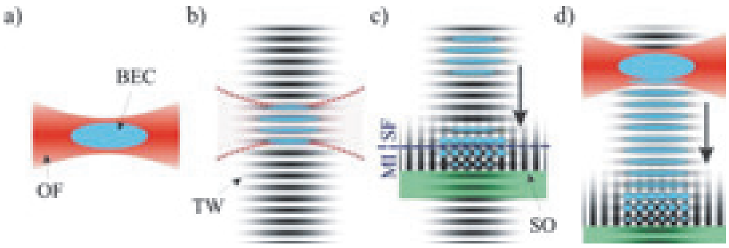
A condensate is prepared in an optical dipole trap and is transferred into a one dimensional standing wave, where it is distributed over several lattice sites. Subsequently, onedimensional lattice is moved towards a surface. Above the sur-face two additional, back reflected laser beams perpendicularly cross the transport wave and form a threedimensional optical lattice with an increasing potential depth. As the condensates traverse this lattice they undergo Mott-insulator transition. From this point on, each lattice site of the three dimensional lattice is populated with exactly one atom, which can be deposited onto surface with nm accuracy. Each atom layer deposited on the surface forms a regularly spaced two-dimensional lattice with a lattice constant λ/2. By moving the substrate after a layer had been deposited, complex periodic single atom structures can be written. The presented strategy describes a very robust method to periodically position single atoms on a surface and to gain technological relevance. E. g. in context of solid state based quantum computers single atom devices are discussed, where periodic arrays of single atoms located beneath an electrode, act as qubits. By applying voltage to the electrodes, the qubits may interact and carry out the desired operation. A further application perspective of this "bottom up" lithography technique might be the production of single atom contacts, which may lead to novel electronic, optical or magnetic devices.

6. Outlook

This short introduction to atom optics exhibits a very versatile and interdisciplinary field in modern optics. Various effects observed in atom optics correspond to the physics studied in light optics. However, due to specific properties of the atoms the atom optical tools exhibit novel features. Bose-Einstein condensates which represent the atom optical analogue to the light optical laser have revolutionized the classical atom optics. Many fundamental quantum effects which arise in very different fields of physics could be observed and discussed using this macroscopic quantum object, and will allow one to address further fundamental problems. Atom optics with weakly interacting, degenerate fermionic atoms opens up a novel field of modern optics, which has no counterpart in classical optic.

Technological application can be found in high precision atom interferometric measurements. Because of their mass and internal structure, atoms are very sensitive to gravitation and external fields. In future experiments, new intense atom laser sources may increase the already achieved enormous precision. Atom lithography allows nowadays creating atom structures on surfaces with a precision of a few tenths of nm. Including new technique as described before, the control of an atom cloud on the single atom basis becomes possible and will lead to new lithographic techniques and surface structures. •

Sven Hensler
Jürgen Stuhler
Tilman Pfau



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Single atom deposition scheme. (a) A BEC is prepared in an optical dipole trap. It is adiabatically transferred into a one-dimensional standing wave (transport wave) (b) and moved towards a substrate (c). Above the substrate the transport wave is perpendicularly crossed by two further standing waves. This light field configuration forms a three-dimensional optical lattice with an increasing potential depth. Thus, as the BEC traverses the optical lattice it undergoes a Mott-insulator phase transition and each lattice site is populated with exact one atom which can be deposited on the surface.

References

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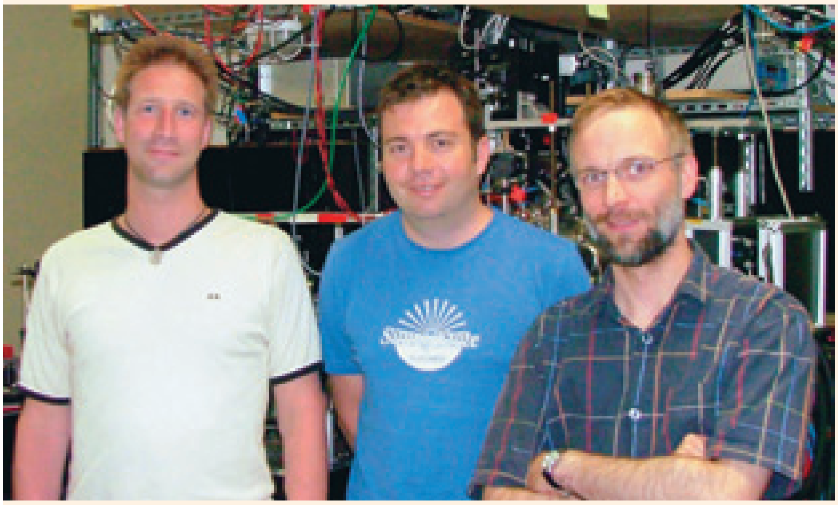
THE AUTHORS



Dr. Sven Hensler (m.)

studied physics in Konstanz. He received his PhD degree in 2004 at the Universität Stuttgart on studies of interactions in ultracold dipolar gases. Since then he has been research associate at the 5th institute of physics. His current research interest is atom lithography and single atom deposition.

Dr. Jürgen Stuhler (l.)

graduated in physics at the University of Konstanz on laser cooling of chromium. As a Marie Curie fellow he spent two years at the LENS (Università di Firenze, Firenze, Italy) building a gravitometer based on atom interferometry. Since 2003 he has been research associate at the Universität Stuttgart his main interests are atom and quantum optics and degenerate quantum gases. He is supported by the Eliteförderprogramm of the Landesstiftung Baden-Württemberg.

Prof. Dr Tilman Pfau (r.)

has been head of the 5th institute of physics in Stuttgart since 2000. He habilitated at the University of Konstanz in 1999. During the last years he was guest scientist in the groups of Prof. C. Cohen-Tannoudji (ENS, France) and Prof. W. Ketterle (MIT, USA). His research interest is atom and quantum optics and basic research on optical technologies and materials including non-classical light sources and detectors and nano-structured optical materials.

Contact

5. Physikalisches Institut, Universität Stuttgart
Pfaffenwaldring 57, 70569 Stuttgart
Tel. +49 (0)711 685 4820
Fax +49 (0)711 685 3810
E-mail: t.pfau@physik.uni-stuttgart.de
Internet: http://www.physik.uni-stuttgart.de/institute/pi/5/

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