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Bose-Einstein condensation of ultracold atomic gases

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Abstract

Bose-Einstein condensation in a dilute gas of sodium atoms has been observed. The atoms were trapped in an optically plugged magnetic trap or in a cloverleaf magnetic trap. Rf induced evaporative cooling increased the phase-space density by six orders of magnitude. We summarize the different techniques used, and discuss recent studies of properties of Bose condensates with an outlook on future developments.

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Introduction

Cooling and trapping of neutral atoms offers exciting new possibilities. Many are related to the fact that the deBroglie wavelength increases with decreasing temperature T as $1/\sqrt{T}$. New physics occurs when the matter wavelength becomes larger than other characteristic length scales.

When the deBroglie wavelength is comparable to atomic dimensions (range of the interaction potential), collisions can no longer be treated classically. They are dominated by weak long-range interactions and characterized by a long duration. Collisions between atoms at milli- and microkelvin temperatures are no longer “billiard ball” collisions, but rather a scattering process between matter waves. Many interesting features of such cold collisions were observed [1]. At sub-microkelvin temperatures, the matter wavelength of atoms becomes longer than the wavelength of light which has profound implications for the interaction between atoms and light. For example, a room temperature atom always “knows” whether it is at a node or anti-node of a light wave, whereas atoms close or below the recoil temperatures are “delocalized” over regions comparable or longer than one optical wavelength. The motion of such atoms is described by a band structure within an optical lattice [2].

Dramatic effects happen for even colder temperatures (micro- and nanokelvin range) and sufficiently high densities, when the deBroglie wavelength becomes comparable to the mean separation between atoms. In this case, the atom waves overlap and the indistinguishability of atoms becomes important. Fermions will form a correlated Fermi sea where collisions and light scattering [3] are suppressed if most of the final states for these processes are already occupied.

Einstein predicted in 1925 that a gas of bosonic particles will undergo a phase transition into a Bose-Einstein condensate if they are cooled to very low temperature [4]. This new phase is characterized by a macroscopic population of the lowest energy level. Bose-Einstein condensation (BEC) is therefore a macroscopic quantum phenomenon like superfluidity and superconductivity. It is distinguished by the coherence of atoms - all atoms in the condensate are indistinguishable and behave identically.

Intuitively one can understand this phenomenon as due to the overlap of matter waves. Because of Heisenberg's uncertainty relation, each atom is smeared out over a region of the thermal deBroglie wavelength. If there is more than one atom per cubic deBroglie wavelength, the atoms "overlap", and the atomic matter wave starts to "vibrate" coherently - a Bose condensate forms.

BEC has been observed in condensed matter physics in superfluid helium [5] and more recently in excitons in Cu_2O [6]. The phenomenon of superconductivity can be related to Bose condensation of electron pairs [7]. Rich novel physics has emerged from the study of these systems. The strong interactions within the solid or the liquid give rise to a variety of interesting phenomena, but also complicate the simple quantum statistical nature of the BEC phase transition. The observation of Bose-Einstein condensation in dilute weakly interacting systems has been one of the major goals in atomic physics in the last years, first pursued in spin-polarized hydrogen [8-10] and more recently in laser-cooled alkali gases. BEC in alkalis has been achieved last year by two groups [11, 12]. A third group has cooled lithium atoms to the quantum-degenerate regime [13, 14]. The successful production of Bose condensates in atomic gases is the starting point for a thorough study of this long-sought novel form of matter.

The study of Bose-Einstein condensation is important because

- Bose-Einstein condensation is a paradigm of quantum statistical physics predicted more than 70 years ago [4].
- A Bose condensate is a novel form of matter with many unknown properties. The ideal (non-interacting) case is well understood, but misses even qualitative features of real, weakly interacting systems [15]. In the wake of the progress of the last few years, many theories have been developed on the formation of a condensate, and its collisional and optical properties [7, 16]. Most theories are approximate and have to be tested experimentally.
- In contrast to other macroscopic quantum phenomena like superconductivity and superfluidity, Bose condensation in atomic gases can be studied at such low densities that perturbative approaches and mean-field theories are accurate [15]. A detailed theoretical understanding of Bose condensation based on first principles might advance our understanding of more complex systems like liquid helium or high-T_c superconductors.
- A Bose condensate is the ultimate source of ultracold atoms. The kinetic energy of a Bose condensate is on the order of one nanokelvin. Such ultracold atoms are ideally suited for precision experiments (determination of fundamental constants, tests of fundamental symmetries) since the slow motion eliminates most systematic effects. This is also important for metrology. Cesium clocks using microkelvin atoms might improve the accuracy of the current frequency standard by two orders of magnitude [17]. Nanokelvin atoms will offer additional improvements.
- A Bose condensate consists of coherent atoms. Such a state of matter has many analogies with coherent photons or laser light and can be regarded as the first realization of an "atom laser". The accumulation of atoms in the Bose condensate can be interpreted as stimulated emission of matter waves. The study of coherent matter waves might become an exciting new subfield of atomic physics [16, 18].

- Bose condensed samples of atoms have potential applications in the field of atom optics, such as atom interferometry, the creation of microscopic structures by direct-write lithography or atom microscopy. With nanokelvin atoms, one could realize the theoretical limit in spatial resolution which is analogous to the diffraction limit in optics.
- When a new regime of ultracold temperatures is explored, there is always the hope of finding something completely unexpected!

Despite the rapid progress in laser cooling over the last few years, the closest approach towards BEC was still missing five orders of magnitude in phase space density. Conventional laser cooling is limited in the lowest temperature by heating due to spontaneous emission, and in density by absorption of scattered light and excited state collisions [19].

Many activities in atomic physics tried to push the temperature and density limits even further. This includes work on sub-recoil cooling techniques [20, 21], optical lattices [22] and far-off-resonant dipole traps [21, 23]. However, the most successful approach was the combination of laser cooling, magnetic trapping and evaporative cooling. The development of these techniques was the focus of the work in our group since 1992 (until 1993 in collaboration with D.E. Pritchard), and in the following, we summarize the essential steps. Related work was pursued in Boulder by E. Cornell and C. Wieman (see e.g. [11, 24-27]).

Laser cooling

A requirement for cooling atoms to ultralow temperatures is to isolate them from all material walls. This is done by trapping atoms with magnetic fields or with laser light inside ultrahigh vacuum chambers. Such traps can store atoms for seconds or even minutes - which is enough time to perform the cooling. Precooling is a prerequisite for trapping - atom traps can confine particles only with a maximum energy of one Kelvin at best, and in many cases the trap depth is just a few millikelvin. The precooling is done by laser cooling. Our experiments start with a thermal beam of sodium atoms at a temperature of 600 Kelvin (or velocity of 800 m/s). The first stage of cooling uses a counterpropagating laser beam which slows the atoms by radiation pressure. An inhomogeneous magnetic fields ensures that the atoms stay in resonance during the deceleration [28-30]. This reduces the velocity of the atoms to 30 m/s, corresponding to a temperature of 1 Kelvin. This is sufficiently cold to capture atoms in a magneto-optical trap (MOT) [31], which consists of six laser beams intersecting in the center of the trap. The laser beams provide restoring forces and compress the atoms to a small cloud of about two millimeter in size. At the same time, the laser beams cool the atoms to about 1 millikelvin.

To trap a large number of atoms in a MOT at high density, we had to overcome the limitations of spontaneous force light traps. In such traps the density is limited by two effects. First, by collisions between ground- and excited-state atoms in which part of the excitation energy is transferred into kinetic energy, resulting in trap loss [1]. Second, by the outward flux of scattered photons which results in a strong repulsive light pressure force [32]. In 1992 we demonstrated a so-called “dark SPOT” (Dark **SP**ontaneous-Force **O**ptical **T**rap) that overcame these problems and allowed us to confine up to 10^{11} atoms at densities approaching 10^{12} cm^{-3} [33]. The limitations of conventional light traps are avoided by optically pumping the trapped atoms into a hyperfine state which does not interact with the trapping light (the so-called dark state). The necessary confinement and cooling are provided by occasionally cycling the atoms back to the "bright" hyperfine state for a short time. Optimization of the population in each of these two states gave rise to a density increase of almost two orders of magnitude. The dark SPOT trap was a key technique in the BEC experiments at JILA [11] and MIT [12].

Evaporative cooling

After collecting atoms in a light trap, an additional cooling step is applied to reduce the temperature (so-called polarization gradient cooling [34]). All the laser beams are then switched off - the missing six orders of phase-space density are gained in complete darkness using evaporative cooling in a magnetic trap.

Evaporative cooling is done by continuously removing the high-energy tail of the thermal distribution from the trap. The evaporated atoms carry away more than the average energy, which means that the temperature of the remaining atoms decreases. The high energy tail is constantly repopulated by collisions, thus maintaining the cooling process. Evaporative cooling is a common phenomenon in daily life - it's how hot water cools down in a bathtub or in a cup of coffee. The technique of evaporative cooling was developed at MIT by Greytak, Kleppner and collaborators as a method for cooling atomic hydrogen which had been pre-cooled by cryogenic methods [35-37]. The essential condition for evaporative cooling is a lifetime of the atomic sample long compared to the collisional thermalization time. Trapped atom clouds are extremely dilute (about ten orders of magnitude less dense than a solid or a liquid) and collisional thermalization times can be on the order of seconds. A major step had been taken in May 1994 when our group and the group at Boulder combined laser cooling with evaporative cooling, extending the applicability of evaporative cooling to alkali atoms. A lifetime much longer than the thermalization time was achieved by combining a Dark SPOT trap with ultrahigh vacuum and a tightly confining magnetic quadrupole trap [38, 39].

In these experiments, the evaporation of atoms was controlled by rf radiation. This technique was proposed by Pritchard [40] and Walraven [41] and first realized by our group [42]. The radiofrequency radiation flips the spin of the atom. As a result, the attractive trapping force turns into a repulsive force and expels the atoms from the trap. This scheme is energy-selective because the resonance frequency is proportional to the magnetic field and therefore to the potential energy of the atoms. In the case of transitions between magnetic sublevels m_F, the resonance condition for the magnetic field strength B is $|g|\, \mu_B\, B = \hbar\, \omega_{rf}$, where g is the g-factor and μ_B the Bohr magnetron. Since the trapping potential is given by $m_F g \mu_B\, [B(r)-B(0)]$, only atoms which have a total energy $E > \hbar\, |m_F|(\omega_{rf}-\omega_0)$ will evaporate. ω_0 is the rf frequency to induce spinflips at the bottom of the trap [43].

Evaporative cooling in a purely optical trap was realized in Stanford in the summer of 1995 [44]. The combination of laser cooling and evaporative cooling was the most important single step towards BEC in dilute atomic gases because it closed the gap between laser cooling which only works at low density and collisional cooling which requires high density. The progress in evaporative cooling of alkali atoms is summarized in Fig. 1.

Tightly confining magnetic traps

The initial demonstrations of evaporative cooling of alkali atoms were done in magnetic traps using a linear potential which provided the tightest confinement possible [38, 39]. However, this so-called spherical quadrupole trap suffers from Majorana flops [45], a trap loss occurring around the zero-magnetic field point - the trap has a tiny "hole" in the center. For large clouds of atoms this trap loss is unimportant, but as the cloud cools, it shrinks and eventually the atoms fall through the hole. This loss process limited the increase in phase space density to a factor of 5 in JILA [26] and 190 at MIT (Fig. 2) [46].

Both the JILA and the MIT group devised new traps to avoid Majorana flops. The JILA group used a rotating magnetic field which moved the hole away from the atoms (TOP trap [26]). Our group realized an atom trap which consisted of a combination of magnetic fields and far-off-resonant light. The hole in the trap was plugged by a blue-detuned laser beam which repels the atoms by the optical dipole force and keeps them away from the regions of very low magnetic fields (Fig. 3). In the experiment, the optical plug was created by an argon-ion laser beam (514 nm) of 3.5 W focused to a diameter of 30 μm. Heating due to photon scattering was suppressed by using far-off-resonant light, and by the fact that the atoms were repelled from the region where the laser intensity was highest. This trap offered a superior combination of large trapping volume and tight confinement. It allowed us to obtain samples of ultracold atoms at unprecedented densities (>10^{14} cm^{-3}) and to evaporatively cool atoms to Bose-Einstein condensation in seven seconds [12] (see below).

The magnetic traps used until recently in BEC experiments had major disadvantages or limitations: The time-dependent rotating field of the TOP trap [26], the sensitivity of the optically plugged trap with respect to shape and position of the optical plug [12], the inflexibility of a permanent magnet trap [13], or the restrictions of a cryogenic environment necessary for superconducting coils [47, 48]. In March 1996, we achieved BEC in a novel "cloverleaf" magnetic trap [49] which overcame those limitations. This trap used dc electromagnets, had excellent optical access, and allowed independent control over the axial and radial confinement. It is a variant of the Ioffe-Pritchard trap [50, 51]: the coils providing the radial gradient surround the two axial coils (the so-called pinch coils) in the form of a cloverleaf. If a Ioffe-Pritchard trap is operated at very low bias field it provides tighter confinement than traps using rotating fields [49]: the radial confinement of these traps is inversely proportional to the value of the bias field. In the case of a rapidly rotating bias field, this field has to be sufficiently large to avoid spinflips which are induced by the rapid rotation of the field direction.

In the last few years, many efforts went into the development of novel atom traps. It is somewhat surprising that, in the end, the most suitable magnetic trap for BEC turned out to be an optimization of the configuration suggested already in 1983 [51], which was used in the late 80's for trapping sodium [52] and atomic hydrogen [47, 48], and later for cesium [25, 53].

Bose-Einstein condensation of a dilute atomic gas

Table I summarizes the observations of BEC reported thus far. In all experiments, the atoms were laser-cooled and loaded into a magnetic trap. Then all laser beams were switched off, and evaporative cooling was forced by lowering the rf frequency. Absorption imaging was used to observe the shrinking cloud.

Fig. 4 shows the shape of the cloud in the optically plugged trap. For high temperatures, the cloud had an aspect ratio of 2:1 due to the anisotropy of the spherical quadrupole field. For temperatures below 20 μK, the cloud broke up into two parts confined to the two minima of the trapping potential (the total trapping potential has a double well due to the anisotropy of the magnetic field). Close to Bose-Einstein condensation, the size of the cloud reached the limit of our optical resolution. This limit was circumvented by suddenly switching-off the trapping potential and imaging the expanding cloud after a delay time of 6 ms. Those images showed the velocity distribution of the cloud. For an ideal gas, the velocity distribution and the spatial distribution differ only by a scaling factor whereas for a weakly interacting cloud, the velocity distribution is determined by the repulsive forces between the expanding atoms.

Fig. 5 shows the velocity distribution of a cloud above and below the transition point. The striking signature of Bose condensation was the sudden appearance of a bimodal velocity distribution when the sample was cooled below the critical temperature of ~2 μK. The distribution consisted of an isotropic thermal distribution and an elliptical core attributed to the expansion of a dense condensate. The same time-of-flight technique was used in the first observation of BEC at JILA [11], whereas at Rice, the condensate was not observed directly, but evidence for cooling into the quantum degenerate regime was obtained from the high optical density and the small size of the atom cloud [13, 14].

Table I demonstrates how powerful evaporative cooling is. It has extended the temperature range for atoms from about one microkelvin down to nanokelvin (the kinetic energy of Bose condensed atoms is 1 nanokelvin or even less), and the density range for laser-cooled atoms from 10^{12} cm^{-3} to more than 10^{14} cm^{-3}. The cooling cycle has been as short as nine seconds, and pure Bose condensates with $5x10^6$ atoms have been observed. We typically cool 0.1% of the atoms collected in the light trap into a pure Bose condensate which is a modest prize for enhancing the quantum occupancy (or phase space density) by twelve orders of magnitude. Some further optimization of the cooling cycle and optical pumping of the atoms before transferring them into the magnetic trap should result in 10^7 to 10^8 Bose condensed atoms with a cycle time of five to ten seconds! The combination of a large number of condensed atoms with short cooling times and ultralow temperatures shows that the current experiments are not just demonstrations of Bose-Einstein condensation, but they are also providing the technology to perform a large variety of studies with nanokelvin atoms.

Study of Bose-Einstein condensates

In the last few months, we have studied several properties of Bose condensates. By evaluating time-of-flight images such as Fig. 5, the total number of atoms, the condensed fraction N_0/N and the temperature T were determined. Below the critical temperature T_c, the condensate fraction should vary as $N_0/N=1-(T/T_c)^3$, in agreement with our results (Fig. 6). Note that this dependence is equivalent to $N-N_0 = 1.202\ (k_BT)^3/(\hbar^3\omega_x\ \omega_y\ \omega_z)$, expressing that the number of atoms in the normal component saturate (ω_i are the harmonic frequencies of the trap). Lowering the temperature forces the atoms which exceed this number to condense. Therefore, the temperature dependence of the condensate fraction is rather a property of the normal dilute Bose gas and is expected to be insensitive to interactions within the dense condensate.

In contrast, the size and density of the condensate strongly depends on the interactions between the atoms. In an ideal gas, the size of the cloud is given by the ground state wavefunction of the system, and the density is proportional to the number of condensed atoms N_0. In a weakly interacting cloud, the size is proportional to $N_0^{1/5}$ and the density scales as $N_0^{2/5}$. This could be directly verified in our experiments where the kinetic energy of the expanding condensate was measured as a function of N_0. After the trap is suddenly switched off, the dominant contribution to the total energy is the repulsive mean-field energy of the dense condensate. The initial kinetic energy is negligible (Thomas-Fermi regime). The kinetic energy of the expanding condensate is therefore a direct measure of the initial interaction energy which is proportional to the density of the condensate. Figure 7 confirms the scaling laws for the density and size of the condensate. Furthermore, the only adjustable parameter in the theoretical fit is the strength of the repulsive interaction between the atoms, the scattering length, which was found to be in agreement with a previous determination [49].

All these experiments were done by switching off the trap and imaging an expanding condensate. This technique is necessarily destructive and probes the condensation phenomenon only in momentum space. However, in an inhomogeneous potential, e.g. in atom traps, the condensate and the normal fraction of a Bose gas are spatially separated [15, 54]. Using dispersive imaging, we have recently observed the spatially localized condensate [55].

Dispersive imaging collects the elastically scattered photons, in contrast to absorption imaging which maps out the spatial distribution of absorbed photons. The scattered photons can be separated from the incident light in the Fourier transform plane of the imaging system; the incident beam comes to a focus there, and can be blocked by a small opaque object. This "dark-ground" method is common in microscopy and is related to "Schlieren" and "phase contrast" methods [56]. In all these methods the image is modified in the Fourier transform plane, enhancing the contrast or the sensitivity for phase objects.

The transmitted probe beam was blocked by a thin wire (0.2 mm), and only photons which were scattered around the wire by the atom cloud were imaged. Fig. 8 shows such images taken around and below the BEC phase transition. It shows the growth of the condensate fraction inside the saturated Bose gas. Dispersive imaging is non-dissipative and does not heat up the condensate. Therefore, several images of the same condensate can be taken. We took two images of the same condensate and varied the probe laser energy. When the signal in the second images deteriorated, $5x10^6$ scattered photons were detected, which is sufficient to take 100 consecutive images of the same condensate. We have some evidence that the limit to the probe pulse energy was set by residual absorption which can be further reduced by using larger probe-light detunings.

This work is the starting point for a systematic study of the optical properties of a Bose condensate [57]. It has been predicted that the linewidth of a Bose condensate shows superradiant broadening [58]. On the other hand, the dispersive signal at far detuning is independent of the linewidth and therefore particularly suited for quantitative measurements. Quantum-statistical effects on the index of refraction have been calculated [59], but are only noticeable near the phase transition, and vanish at T=0.

Dispersive light scattering is a non-destructive method. Strictly speaking, however, quantum mechanics does not allow non-perturbative measurements. Although dispersive scattering does not heat up the cloud and destroy the condensate, it will change the phase of the condensate due to frequency shifts by the ac Stark effect. This should still allow a quantum-non-demolition measurement of the number of condensed atoms. This would be the inverse situation compared to quantum non-demolition measurements in microwave cavities where the photon number is determined from the phase shift of Rydberg atoms passing through the cavity [60].

Conclusions

Bose-Einstein condensation in dilute atomic gases has been observed only one year ago. The first observations have confirmed Einstein's predictions and demonstrated that cooling and trapping techniques have been developed to reach the quantum-statistical regime. The developments since then have already shown that BEC is well on its way to becoming a new subfield of atomic and condensed matter physics: Bose condensed atoms will be used as bright atom sources for precision experiments, BEC represents a major step towards the atom laser, the study of Bose condensates will provide crucial tests for many-body theories of interacting particles and for thermodynamics in finite systems, and finally, Bose condensates open a new window into the quantum world by providing large quantum objects (up to 0.3 mm in size) which might show superfluidity and macroscopic quantum interference phenomena.

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Table and table caption:

	JILA 95 [11]	MIT 95 [12]	MIT 96 [49]	Rice 95 [13]
Atom	^{87}Rb	Na	Na	^{7}Li
Scattering length [nm]	+ 6 nm	+ 5 nm	+ 5 nm	- 1.5 nm
Trap	TOP	Opt. plugged mag. trap	Cloverleaf mag. trap	Permanent mag. trap
$B''_x B''_y B''_z$ $[(10^3\ G/cm^2)^3]$	27	$4x10^6$	100	1
first BEC	June 95	Sept. 95	March 96	July 95
Evidence for BEC	TOF	TOF	TOF direct imaging	Halo?
N_c	$2x10^4$	$2x10^6$	$15x10^6$	$2x10^5$
T_c [nK]	100	2,000	1,500	400
n_c [cm^{-3}]	$2x10^{12}$	$1.5x10^{14}$	$1x10^{14}$	$2x10^{12}$
N_0	2,000	$5x10^5$	$5x10^6$	?
Cooling Time	6 min.	9 s	30 s	5 min.
condensed atoms/s	6	60,000	200,000	?
lifetime	≈ 15 s	≈ 1 s	≈ 20 s	≈ 20 s

Table I: Comparison of BEC experiments reported thus far.

Figure captions:

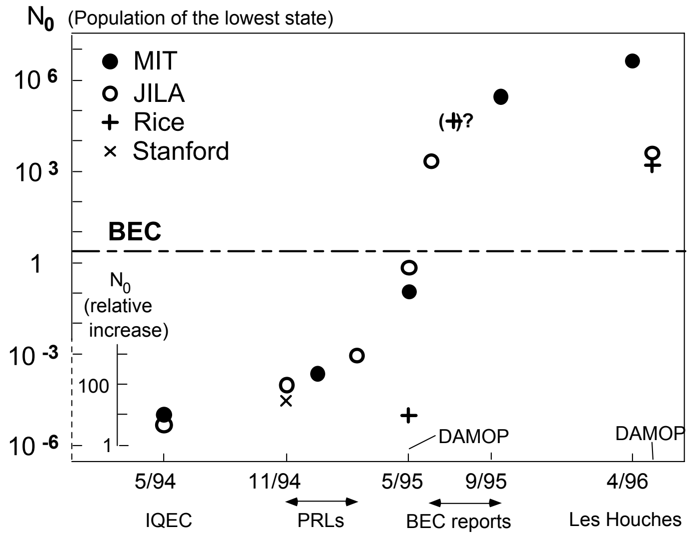

Figure 1: Progress in evaporative cooling of alkali atoms. The combination of laser cooling and evaporative cooling of alkali atoms was the essential technique for the observation of BEC in dilute atomic gases. This diagram shows all experiments reported thus far on evaporative cooling of alkali atoms. The number of atoms in the lowest quantum state is proportional to the so called phase-space density, and has to exceed a critical number of 2.612 to achieve Bose-Einstein condensation. For $N_0<10^{-3}$, the increase in phase-space density is plotted.

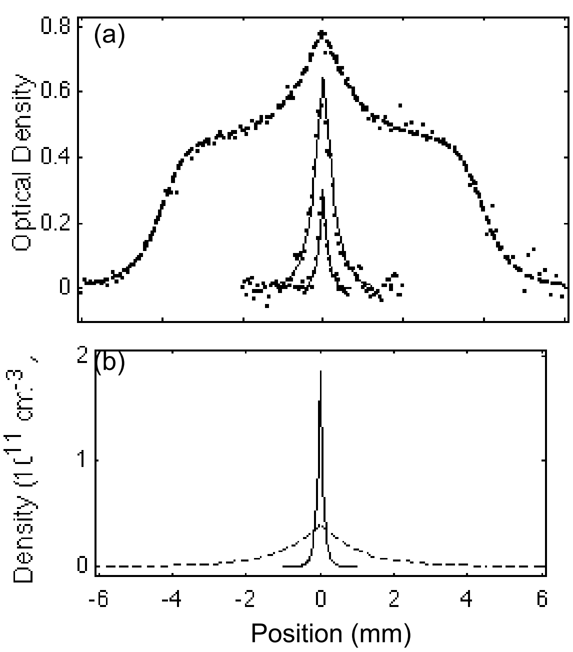

Figure 2: Evaporative cooling in a spherical quadrupole trap [46]. The figure shows the optical density (a) and density (b) before and after evaporative cooling. The density is obtained from a

fit to the optical density. The initial temperature was reduced by a factor of twelve. At the same time, the density increased, despite the loss in the number of trapped atoms.

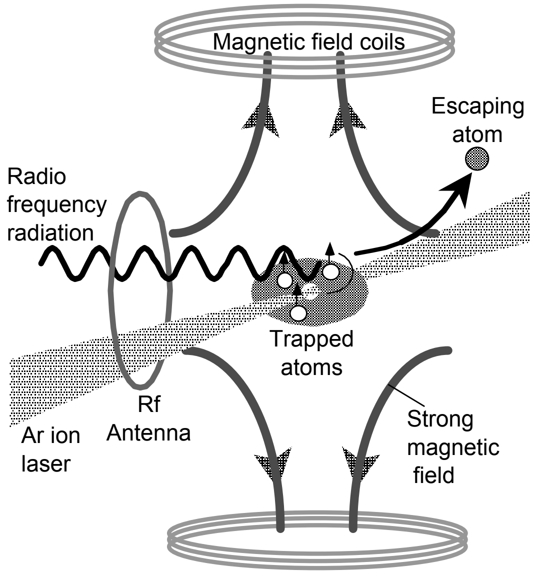

Figure 3: Experimental setup for cooling atoms to Bose-Einstein condensation [12]. Sodium atoms are trapped by a strong magnetic field, generated by two coils. In the center, the magnetic field vanishes which allows the atoms to spin-flip and escape. Therefore, the atoms are kept away from the center of the trap by a strong (3.5 W) Ar^+ laser beam ("optical plug") which exerts a repulsive force on the atoms. Evaporative cooling is controlled by radio-frequency radiation from an antenna. The rf selectively flips the spins of the most energetic atoms. The remaining atoms rethermalize (at a lower temperature) by collisions among themselves. Evaporative cooling is forced by lowering the rf frequency.

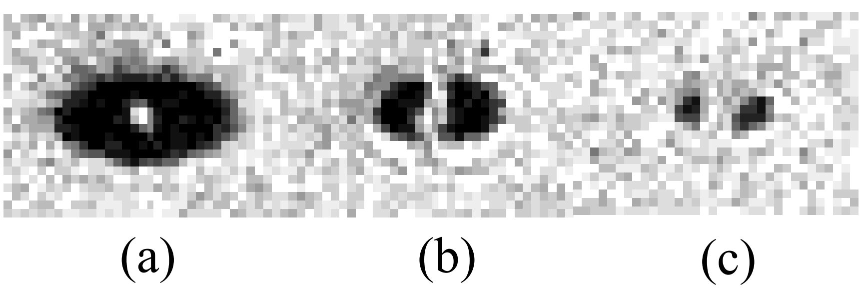

Figure 4: Absorption images of atom clouds trapped in the optically plugged trap [12]. Cloud (a) is already colder than was attainable without the "plug" (Ar ion laser beam). Cloud (b) shows the break-up of the cloud into two "pockets" in the two minima of the double-well. The size of cloud (c) reaches the optical resolution of the imaging system (< 10 μm) still absorbing 90 % of the probe light. This sets an upper bound on temperature (< 10 μK) and a lower bound on density (5×10^{12} cm^{-3}). The width of each image is about 120 μm.

(see attached)

Figure 5: Two-dimensional probe absorption images, after 6 ms time of flight, showing evidence for BEC. (a) is the velocity distribution of a cloud cooled to just above the transition point, (b)

just after the condensate appeared, (c) after further evaporative cooling has left an almost pure condensate. The width of the images is 0.9 mm.

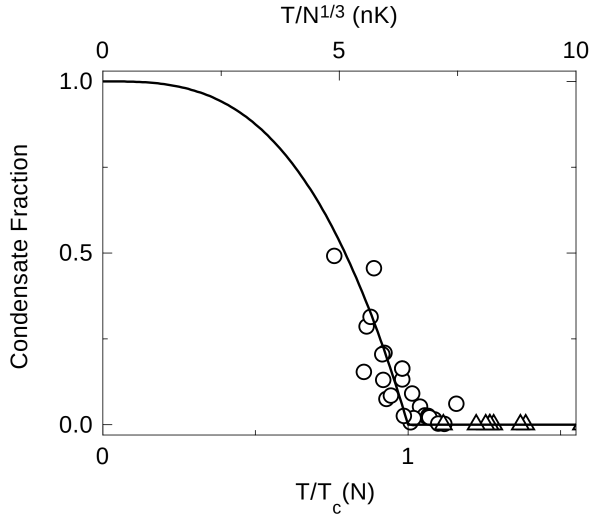

Figure 6: Condensate fraction versus normalized temperature T/T_c. Solid line: theoretical curve. The experimental data was determined from fits to time-of-flight images.

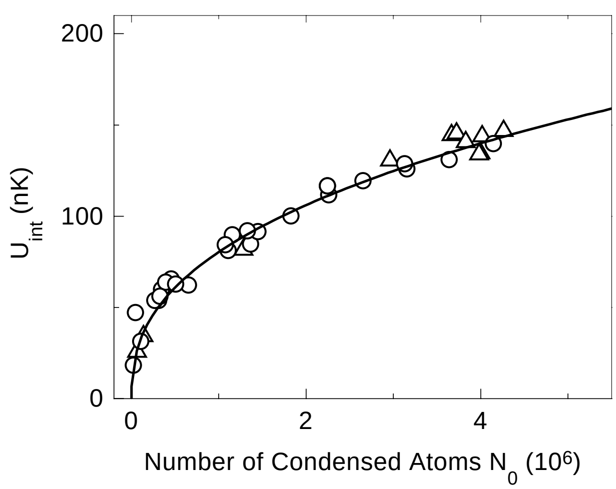

Figure 7: Mean-field energy per condensed atom versus the number of atoms in the condensate. The solid line is the theoretical prediction proportional to $N_0^{2/5}$ with only the scattering length as adjustable parameter.

(see attached)

Figure 8: Direct observation of Bose-Einstein condensation of magnetically trapped atoms by dispersive light scattering. The figures show clouds with a condensate fraction that is increasing

from close to 0% (left) to almost 100 % (right). The signal for the normal component is rather weak and interferes with the speckle pattern of stray laser light, giving it a patchy appearance.