Direct, Non-Destructive Observation of a Bose Condensate

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Abstract

The first spatial observation of a Bose condensate is reported. The separation between condensed and normal components was observed inside a magnetic trap using dispersive light scattering. This technique is non-destructive, and about a hundred images of the same condensate can be taken. Furthermore, the width of the angular distribution of scattered light increased suddenly at the phase transition.

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Bose-Einstein condensation is characterized by a macroscopic population of the quantum-mechanical ground state below a critical temperature. It is the origin of macroscopic quantum phenomena such as superfluidity in liquid helium [1]. For a homogeneous sample, Bose-Einstein condensation is sometimes called "condensation in momentum space" [2] since it does not lead to a spatial separation between the condensate and the normal component. However, in any inhomogeneous potential, e.g., in atom traps or even in the earth's gravitational field, the condensate and the normal fraction of a Bose gas are spatially separated [2,3]. So far, Bose condensation has only been seen in momentum space: the condensate fraction of liquid helium was determined by neutron scattering [4], condensation of excitons was deduced from the observed energy distribution of the excitonic particles [5], and BEC in dilute atomic gases was detected by observing the velocity distribution of freely expanding Bose condensates [6,7]. In this paper we report the first direct and non-destructive observation of the spatially localized condensate, in a gas of magnetically trapped sodium atoms.

Bose condensates of dilute atomic gases are a new form of quantum matter. The pioneering work towards Bose-Einstein condensation (BEC) in atomic gases was done with spin-polarized hydrogen using magnetic trapping and evaporative cooling [8]. Work at JILA [9] and at MIT [10] succeeded in combining these techniques with laser cooling [11], which resulted in the observation of BEC in rubidium in June [6] and in sodium in September of 1995 [7]. Lithium has also been cooled to the quantum degenerate regime [12]. Since these developments there has been a flurry of both theoretical and experimental activities [13].

In atom traps, the condensation phenomenon results in the formation of a dense core of atoms in the ground state of the system surrounded by the normal component — analogous to droplet formation in a saturated vapor. Earlier attempts in our laboratory to observe the Bose condensate directly by absorption imaging failed because of the high optical density of the atom cloud near the critical temperature. For typical parameters of our experiment (see below) the peak optical density (D_0) for resonant light is around 300, corresponding to a transmission coefficient of e^{-300}. Thus the probe light is completely absorbed even in the wings of the spatial distribution, preventing direct imaging of the condensate. Detuning of the light, which reduces the absorption, reveals major image distortions due to dispersive effects: the condensate acts as a lens and strongly deflects the light. However, by employing the so-called "dark-ground" imaging technique (see [14] and below) the dispersively scattered light can be used to clearly image the condensate, as we demonstrate in this paper.

Let us briefly summarize why dispersive imaging has significant advantages over absorption methods for the imaging of small and dense clouds ($D_0 \gg 1$). To obtain a good absorption signal, one would like to detune the probe light until the off resonant optical density is near unity. The off-resonant optical density is given by $D = D_0/\Delta^2$, where the detuning Δ from the resonant frequency ω_0 is $\Delta = 2(\omega - \omega_0)/\Gamma$, with Γ being the natural linewidth. The maximum phase shift δ of the transmitted wave is $\delta = D_0/2\Delta$, and thus for $D \sim 1$ the phase shift will be $\delta \sim \sqrt{D_0}/2$. Such a large phase shift is indicative of lens-like refraction, which bends the incident probe light beyond the cloud's diffractive scattering angle. If the spatial resolution of the imaging system is well matched to the small size of the cloud, this refracted light does not reach the camera and is lost; therefore, absorption images of small and dense clouds are unavoidably degraded. In order to use the imaging system at its nominal resolution, detunings on the order of D_0 are necessary, where absorption signals are negligible but dispersive phase shifts are on the order of unity. The signal in dispersive imaging depends upon this phase shift, yielding a viable method for probing dense and small clouds.

This argument can also be understood by considering the small dense cloud to be a lens. A sphere of radius R and index of refraction n acts as a lens having focal length f with $1/f = 2(n-1)/R$ [14]. The phase shift δ through the center of the lens is $\delta = 4\pi R(n-1)/\lambda$, yielding $f = 2\pi R^2/\delta\lambda$, and the maximum deflection angle θ for the light is approximately $\theta \approx R/f = (2\delta/\pi) \times (\lambda/4R)$. If the phase shift δ exceeds $\pi/2$, there will be deflection of light due to *refraction* which exceeds the scattering angle $\lambda/4R$ due to *diffraction*. As long as the imaging system collects and images the refracted light, quantitative absorption imaging is possible. However, the radius R of the smallest object which can be resolved is usually determined by the collection angle α of the optics to be $R = \lambda/2\alpha$. Additional refraction by the object will scatter light out of the optical system and impede absorption measurements. Therefore, dispersive refraction limits the use of absorption imaging to objects $\approx 2\delta/\pi$ times larger than the diffraction-limited value of $R = \lambda/2\alpha$.

Dispersive scattering is the coherent forward scattering of light. In a homogeneous medium, the scattered light interferes constructively only in the direction collinear with the incident light. The interference with the transmitted beam results in a phase shift and is described by the usual theory for the index of refraction [14]. In contrast, for an inhomogeneous medium of extension $2R$, such as a trapped cloud of atoms, the coherently scattered light interferes constructively in an angular region $\lambda/2R$. The scattered light 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 [14]. In all these methods the image is modified in the Fourier plane, enhancing the contrast or the sensitivity for phase objects.

In our experiment, sodium atoms are cooled down to Bose-Einstein condensation using a combination of laser cooling, magneto-optic trapping, magnetic trapping and evaporative cooling. The atom cloud is confined in a novel magnetic trap which uses "cloverleaf" coils to generate the inhomogeneous magnetic field [15]. Near the bottom of the trap, the trapping potential is harmonic and axially symmetric, with independently adjustable axial and radial confinement. Evaporative cooling is controlled by continuously reducing the frequency of rf radiation. The rf field induces spin-flips at a specific value of the magnetic field where the condition for electron spin resonance is met. Since the spin-flips reverse the sign of the magnetic force upon the atoms, the spin-flipped atoms are ejected from the trap [16,17]; in this way the rf determines an effective trap depth. The escape of the hottest atoms from the trap, in combination with rethermalization of the remaining atoms through elastic collisions, cools the sample (evaporative cooling) and leads to a temperature which is about 10% of the trap depth.

Typically, we reach the BEC phase transition with 1.5×10^7 atoms in the $F = 1, m_F = -1$

state, at a temperature of $1.5\,\mu$K and a number density of $1 \times 10^{14}\,\text{cm}^{-3}$. Further cooling results in the formation of a nearly pure condensate with 5×10^6 atoms [15]. Temperature and number are determined by a time-of-flight technique where the trap is suddenly switched off and the cloud expands ballistically. The expanding cloud becomes dilute, and quantitative absorption images can be taken. The temperature is derived from the rms velocity of the cloud's normal component, whereas the number is obtained from the total light absorption.

To image the cloud using dispersive light scattering, the probe light is red-detuned by 1.71 GHz ($\Delta = -342$) from the $F = 1$ to $F = 2$ transition [18]. The cloud is imaged onto a CCD sensor using a lens system with a resolution of $5\,\mu$m. A thin wire (0.2 or 1.0 mm) in the Fourier plane of the lens system blocks the transmitted unscattered light ("dark-ground" imaging). The images were obtained by exposing the trapped atoms to weak probe light for 0.5 s after the loading and cooling procedure. For each image, a new cloud was loaded and cooled to a progressively lower temperature. Figure 1 shows the growth of the condensate fraction within the saturated Bose gas. The number of atoms in the normal component saturates at $1.202(kT/\hbar\bar{\omega})^3$ [19], where $\bar{\omega}$ is the geometric mean of the three harmonic trapping frequencies. Lowering the temperature forces the atoms which exceed this number to condense, similar to droplet formation in a saturated vapor. This process was directly observed in Fig. 1. Fig. 2 shows the effective area of the cloud as observed in dark-ground imaging, versus final rf frequency which is approximately linearly related to the temperature. The sudden decrease of the area at the onset of BEC (at an rf frequency of 1200 kHz) is a sensitive indicator for the phase transition.

Dispersive imaging is a non-destructive technique and allows many pictures of the same condensate to be taken. Absorption imaging relies on incoherent large-angle (Rayleigh and Raman) scattering. Each scattering event heats up an atom on average by an energy of $(\hbar k)^2/m = 2.3\,\mu\text{K} \times k_B$, which is two single-photon recoil energies ($\hbar k$ denotes the photon momentum and m the atomic mass). In dispersive scattering, the photons are elastically scattered by only a small angle $\lambda/4R$ which is typically 0.02 radians in our experiment. The recoil energy of this process is about 0.5 nK, two thousand times smaller than the single-photon recoil energy. Furthermore, when the probe pulse duration is much longer than the oscillation period in the trap, the momentum transfer to an individual atom averages out; hence no heating is associated with the coherent forward scattering of light. This can be regarded as a Mössbauer effect, where the momentum is absorbed by the trap and not by individual atoms. An alternative explanation uses the concept of light forces. For red-detuned light, the incident plane wave is made convergent (since the index of refraction is greater than one). As a consequence, the light exerts an outward force on the atoms through the stimulated light force (or the optical dipole force). If this force is switched on and off adiabatically there is no heating.

Figure 3(a) proves that dispersive imaging can be non-destructive. The same condensate was imaged twice with a delay time of one second without an observable reduction in the signal. When the incident pulse energy of the probe light was increased to $2\,\mu\mathrm{J/cm}^2$, the signal in the second image deteriorated. At this energy, 5×10^6 scattered photons were detected, which is sufficient to take 100 consecutive images of the same condensate. We estimate that under these conditions the probability for off-resonant absorption is about 4%, implying an energy transfer of around 100 nK per atom in the cloud. It is therefore likely that the limit to the probe pulse energy was set by residual absorption and can be further reduced by using larger probe-light detunings.

Very short probe pulses would provide good temporal resolution at the expense of suppressing the Mössbauer effect discussed earlier. For probe durations shorter than the oscillation time, the atoms should behave as free particles and receive recoil kicks of 0.5 nK per forward scattered photon. For our conditions, this energy is negligible compared to the heating due to residual absorption. In agreement with this, no difference in the maximum non-destructive probe pulse energy was observed when the pulse duration was varied between 2 and 200 ms. The shortest exposure time was comparable to the radial oscillation period (3 ms). Shorter pulses with the same energy could not be applied due to limitations in probe power, but are possible and would give even better temporal resolution.

The ability to take several non-destructive images will be very useful for the study of the dynamics of a single condensate, such as its formation and decay. If studies are done destructively, each time step is taken with a new sample and shot-to-shot fluctuations may be limiting. Figure 3(b) shows an example of a condensate which was adiabatically expanded between the two exposures.

The angular distribution of the scattered light is anisotropic due to the elongated shape of the cloud. For a dilute sample, the angular distribution is determined by the Fourier transform of the spatial distribution. At low density, the scattering is weak and covers an angle of about $\lambda/4R$. Increasing the density increases only the intensity of the scattered light. However, when the phase shift across the sample approaches $\pi/2$, the cloud behaves as a lens and refracts the light with an angular deflection larger than $\lambda/4R$ (as estimated above). Further increase of the density will increase the deflection angle.

At 1.71 GHz detuning and an estimated resonant optical density of 300, the maximum phase shift is about 0.5, which means we are still in the diffractive regime, but close to the transition where refraction becomes important. Between 10% and 100% of the incident probe light intensity was deflected by the condensate.

By focussing the camera onto the Fourier plane of the first imaging lens, the angular distribution of scattered light could be directly recorded. We observed that the BEC phase transition is accompanied by an increase of the scattering angle. The rms scattering angle of the thermal cloud, $\approx 7\,\mathrm{mrad}$, corresponds to the diffraction angle of a cloud with radial diameter 20 μm, in agreement with the size of a $1.5\,\mu$K cloud in the magnetic trapping potential (Fig. 4). The angular scattering pattern of the condensate has an rms width of $\approx 20\,\mathrm{mrad}$. This is in agreement with the size and shape of the condensate as calculated using the nonlinear Schrödinger equation and the Thomas-Fermi approximation [20].

The results presented here demonstrate convincingly that dispersive light scattering is an important method to study BEC. Although we have emphasized qualitative aspects in the present study, quantitative measurements are possible because the signal in dispersive imaging depends only on the phase shift δ; the phase shift is an absolute measure of the line-of-sight integrated atomic density. For small phase shifts, which are obtained at large detunings, the fraction of scattered light in dark-ground imaging is δ^2. A signal linear in δ can be obtained by implementing the phase contrast method.

The work reported in this paper is the starting point for a systematic study of the optical properties of a Bose condensate [21]. The current study was performed with 1.71 GHz detuned light, generated with an acousto-optical modulator. Additional measurements at 100 MHz detuning showed several fringes in dark ground images, due to phase shifts $\delta > 2\pi$. We are currently setting up an independent dye laser to characterize the optical properties of the condensate starting from very large detunings. It has been predicted that the linewidth of a Bose condensate shows superradiant broadening [22]. 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 [23], but are only noticeable near the phase transition, and vanish at T=0.

We have presented dispersive light scattering as 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 its phase due to frequency shifts by the ac Stark effect. This should still allow a quantum non-demolition measurement of the number of condensed atoms, and would be the inverse situation compared to related measurements in microwave cavities where the photon number is determined from the phase shift of Rydberg atoms passing through the cavity [24].

UNCITED NOTE

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FIGURES

FIG. 1. Direct observation of Bose-Einstein condensation of magnetically trapped atoms by dispersive light scattering. The probe laser beam propagates along a radial direction of the trap. The figures show clouds with a condensate fraction that is increasing from close to 0% (left) to almost 100% (right). This series was taken at axial and radial field curvatures of $100\,\mathrm{G/cm^2}$ and $3\,\mathrm{kG/cm^2}$, respectively, resulting in an aspect ratio of the trapped cloud of about 6. The signal for the normal component is rather weak and interferes with the speckle pattern of stray laser light, giving it a patchy appearance.

FIG. 2. Effective area of the atom cloud in dark-ground imaging versus final rf frequency. The effective area is defined as the total amount of scattered light divided by the peak scattered intensity. The sudden decrease in the effective area indicates the BEC phase transition.

FIG. 3. Demonstration of non-destructive imaging. The left and right figures in (a) are images of the same condensate taken one second apart. The axial and radial field curvature were $100\,\mathrm{G/cm^2}$ and $30\,\mathrm{kG/cm^2}$, respectively, resulting in an aspect ratio of the trapped cloud of about 20. (b) demonstrates the observation of the dynamics of a single condensate. The two pictures were taken six seconds apart during radial decompression of the cloud. The final radial field curvature (right) was $3\,\mathrm{kG/cm^2}$.

FIG. 4. Angular distribution of the scattered light. The trapping field curvatures are the same as in Fig. 3(a). The figure shows the intensity of the scattered light in the Fourier plane of the imaging system, i.e. the intensity as a function of the radial and axial scattering angles. The upper image is for a cloud just above BEC, the lower one for an almost pure condensate. The central parts of the images are obscured by a 1.0 mm wire, blocking the undeflected probe beam.