Bose-Einstein condensation in dilute atomic gases: atomic physics meets condensed matter physics

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Abstract

Bose-Einstein condensed atomic gases are a new class of quantum fluids. They are produced by cooling a dilute atomic gas to nanokelvin temperatures using laser and evaporative cooling techniques. The study of these quantum gases has become an interdisciplinary field of atomic and condensed matter physics. Topics of many-body physics can now be studied with the methods of atomic physics. Many long-standing predictions of the theory of the weakly interacting Bose gas have been verified, including thermodynamic properties of the phase transition and dynamic properties such as shape oscillations and sound propagation. Stimulated light scattering was used to determine the dynamic structure factor both in the phonon and free-particle regime. Atomic Bose condensates show a variety of novel phenomena which include multi-component spinor condensates, magnetic domain formation, miscibility and immiscibility of quantum fluids, and finite-size effects.

Keywords: Bose-Einstein condensation; collective excitations; light scattering; spinor condensates

1. Introduction

To receive the Fritz London Memorial Award is very special to me—it is the token of a wonderful experience I have had during the last few years. I was trained as an atomic physicist and, in the early '90s, focused on the development of trapping and cooling techniques trying to reach lower temperatures of atomic gases. In 1995, while cooling gaseous clouds to sub-microkelvin temperatures, we realized an intriguing new many-body system—the gaseous Bose-Einstein condensate. The years since then have been a rewarding intellectual experience—to learn and study the old and new physics of a new quantum fluid. But those years have also been an enormous personal experience. I made many new friends and got to know many new colleagues who taught me about low-temperature physics. I want to thank all of them, and also acknowledge the past and present collaborators who have shared both the excitement and the hard work: M.R. Andrews, A.P. Chikkatur, K.B. Davis, D.S. Durfee, A. Görlitz, S. Gupta, Z. Hadzibabic, S. Inouye, M.A. Joffe, M. Köhl, C.E. Kuklewicz, A. Martin, M.-O. Mewes, H.-J. Miesner, R. Onofrio, T. Pfau, D.E. Pritchard, C. Raman, D.M. Stamper-Kurn, J. Stenger, C.G. Townsend, N.J. van Druten, and J. Vogels.

This award is even more special to me since it carries the name of Fritz London. After Bose-
Einstein condensation was predicted in 1925, many people regarded it as a mathematical oddity. It was Fritz London who connected it with a real phenomenon when he suggested in 1938 that the recently discovered superfluidity of liquid helium was related to Bose-Einstein condensation [1,2].

BEC in dilute atomic gases is a new subfield which is interdisciplinary between atomic and condensed matter physics. This subfield deserves the name ultralow temperature physics, since the temperatures of the gaseous BEC systems are usually in the nanokelvin range. Ultracold atomic gases and nuclear spin systems (for which picokelvin spin temperatures were obtained in Helsinki [3]) are the coldest matter studied so far. Alternatively, one might call the gaseous BEC ultralow density condensed matter physics. Bose-Einstein condensation in atomic gases is observed at number densities of $10^{14} \text{ cm}^{-3}$ which are similar to a room temperature gas at a pressure of $10^{-2} \text{ mbar}$! The low density is crucial for the (meta-) stability of the cold atomic gas against inelastic collisions, in particular three-body recombination. The system develops many-body correlations at such low density because the thermal de Broglie wavelength at nanokelvin temperatures exceeds $1 \mu\text{m}$, more than the average distance between atoms.

Research on gaseous BEC can be divided into two areas: In the first (which could be labeled “The atomic condensate as a coherent gas”, or “Atom lasers”), one would like to have as little interaction as possible—almost like photons in an optical laser. Thus the experiments are preferentially done at low densities. The Bose-Einstein condensate serves as an intense source of ultracold coherent atoms for experiments in atom optics, in precision studies or for explorations of basic aspects of quantum mechanics. The second area could be labeled as “BEC as a new quantum fluid” or “BEC as a many-body system”. The focus here is on the interactions between the atoms which are most pronounced at high densities. In the spirit of the London Award Lecture, I will put the emphasis on the second area and illustrate with some examples how novel many-body physics is explored with the methods of atomic physics.

2. Studies of Bose-Einstein condensation

Since long, macroscopic quantum phenomena have been studied in strongly interacting systems, most notably in the superfluids $^4\text{He}$ and $^3\text{He}$, and in superconductors. The quest to realize BEC in a dilute weakly interacting gas was pursued in at least three different directions: liquid helium, excitons and atomic gases. Experimental [4] and theoretical work [5] showed that the onset of superfluidity for liquid helium in Vycor shows features of dilute-gas Bose-Einstein condensation. At sufficiently low coverage, the helium adsorbed on the porous sponge-like glass behaved like a dilute three-dimensional gas. Excitons, which consist of weakly-bound electron-hole pairs, are composite bosons. The physics of excitons in semiconductors is very rich and includes the formation of an electron-hole liquid and biexcitons. As nicely discussed in [6,7], there are systems, most notably Cu$_2$O, where excitons form a weakly interacting gas with a lifetime long enough to equilibrate to a Bose-Einstein distribution and to show evidence for Bose-Einstein condensation [8].

Dilute atomic gases are distinguished from the condensed-matter systems discussed above by the absence of strong or complex interactions. Interactions at the density of a liquid or a solid considerably modify and complicate the nature of the phase transition. Early suggestions [9,10] that spin-polarized hydrogen would remain gaseous down to zero temperature triggered several experimental efforts, most notably by Silvera and Walraven in Amsterdam [11], and Greytak and Kleppner at MIT who finally accomplished BEC in 1998 [12,13]. Major efforts have also been underway to reach quantum degeneracy in a two-dimensional gas of spin-polarized hydrogen which was observed in 1998 by the Turku/Moscow collaboration [14]. Most of the current efforts focus on alkali atoms. BEC in alkali gases was observed
in 1995, first for rubidium in Boulder [15], and a few months later for sodium at MIT [16]. At the same time, evidence for quantum degeneracy in lithium was obtained by the Rice group [17]. Since then, more than fifteen other groups have generated alkali Bose condensates of either rubidium or sodium [18].

Alkali atoms are precooled by laser cooling and collected in an optical trap. After transfer into a magnetic trap, further evaporative cooling reduces the temperature to 1 µK or below where the BEC phase transition is reached [19,20]. Experiments with alkali atoms don’t need cryogenic cooling. The combination of ultrahigh vacuum and magnetic trapping provides enough insulation between nanokelvin atoms and room-temperature walls. Thermal radiation is not important because the atoms can only absorb the negligible fraction of the impinging radiation which is resonant with an atomic transition. A room-temperature vacuum chamber allows for easy optical access to the atoms and the implementation of powerful imaging techniques.

Atom clouds are observed either by absorptive or dispersive techniques. In the first case, the shadow cast by the atom cloud is imaged onto a CCD camera. In the latter case, dispersively scattered photons are collected creating an image of the spatially varying index of refraction. The BEC phase transition can be directly observed in the spatial domain [21]. Fig. 1 shows a series of such spatial images above and below the phase transition. They show the sudden appearance of a high-density core of atoms in the center of the distribution—the Bose-Einstein condensate. Lowering the temperature further, the condensate number grows and the thermal wings of the distribution become shorter. Finally, the temperature drops to the point where only the central peak remains.

Similarly, the BEC phase transition can be observed by imaging the shadow cast by an atom cloud which expands ballistically after suddenly switching off the magnetic trap. The signature of BEC is the sudden appearance of a slow component with anisotropic expansion [15,16]. This can be regarded as observing BEC in momentum space.

### 3. Sound in gaseous Bose-Einstein condensates

Collective excitations of liquid helium played a key role in determining its superfluid properties [22,23]. The low-lying excitations are phonon-like and are characterized by the speed of sound. In a Bose-Einstein condensate, the speed of sound could be directly determined by creating localized density perturbations using a focused far-off-resonant blue detuned laser beam [24]. Such light creates a repulsive potential due to the ac Stark effect. The repulsive optical dipole force expelled atoms from the center of the condensate, creating two density peaks which propagated symmetrically outward. Fig. 2 shows the propagation of density perturbations observed by sequential phase-contrast imaging of a single trapped cloud. We observed one-dimensional axial propagation of sound at a constant velocity near the center of

![Fig. 1. Phase contrast images of a trapped sodium gas across the BEC phase transition. As the final radio frequency used in evaporative cooling is lowered, the temperature is reduced (left to right). Images show the onset of Bose condensation, the growth of the condensate fraction and contraction of the thermal wings, and finally a pure condensate with no discernible thermal fraction. The axial and radial frequencies are about 17 and 230 Hz, respectively.](image-url)
Fig. 2. Observation of sound propagation in a Bose-Einstein condensate. (top) Basic scheme for exciting wave packets in a condensate. A condensate is confined in the potential of a magnetic trap. At time $t = 0$, a focused, blue-detuned laser beam is suddenly switched on and, by the optical dipole force, creates two positive perturbations in density which propagate at the speed of sound for $t > 0$. (bottom) Profiles through images taken every 1.3 ms, beginning 1 ms after perturbing the trapping potential by focusing a far-off resonant laser beam into the center of the cloud. The perturbation created the “dip” in the center, and two “blips” traveled outward with the speed of sound. Figures adapted from ref. [24].

The density dependence of the speed of sound $c_s$ was studied using adiabatically expanded or compressed condensates, yielding maximum condensate densities $n_0$ ranging from 1 to $5 \times 10^{14}$ cm$^{-3}$. The data were in good agreement with the prediction of Bogoliubov theory, $c_s = (4\pi \hbar^2 an/m^2)^{1/2}$ where $m$ is the atomic mass, $a$ the scattering length, and $n$ the radially averaged density [25].

These experiments were done with almost pure condensate (at temperatures well below the critical temperature). The spatial extent of the propagating density perturbations was about 20 $\mu$m.

For a more general discussion of sound, we have to include finite temperatures and a hierarchy of length scales. The presence of the normal cloud in addition to the condensate can be described by a two-fluid model, similar to the normal and superfluid phases of liquid helium. Two fluids should give rise to two different modes. In the collisionless regime, the wavelength of the excitation is much smaller than the mean-free path $\lambda_{ex} \ll l_{mfp}$. This regime applies at zero temperature and at low densities of the thermal cloud. In this regime, the thermal cloud behaves ballistically and does not show collective (sound-like) behavior whereas the condensate shows Bogoliubov sound (sometimes also called zero sound).

At higher densities of the normal component, when $\lambda_{ex} \gg l_{mfp}$, both collective modes are hydrodynamic, and one expects two phonon-like excitations which are the in-phase and out-of-phase oscillations of two fluids (the normal fraction and the superfluid). The presence of two hydrodynamic modes is similar to the case of bulk superfluid $^4$He, where they are known as first and second sound. Superfluid $^4$He has a small coefficient of thermal expansion. Thus the two eigenmodes decouple into density modulations (first sound) and temperature modulations (second sound), with both fluids participating equally in both modes. In contrast, a gas has a large coefficient of thermal expansion. This results in the oscillations of each fluid being nearly uncoupled. The in-phase oscillation, which is analogous to first sound, involves mainly the thermal cloud. The out-of-phase oscillation, which is analogous to second sound, is confined mainly to the condensate [26,27].

First and second sound occur only in the so-called hydrodynamic regime, where the mean-free path is shorter than the wavelength of sound. The longest possible wavelength is given by the size of the sample. These low-lying excitations are observed as shape oscillations. The early studies of sound in a BEC were in the collisionless regime. In the finite-temperature experiment at MIT, the hydrodynamic regime was approached for the first time [28]. The onset of hydrodynamic behavior was
indicated by collisional frequency shifts and damping of the thermal cloud signaling the transition towards first sound. An anti-symmetric dipole oscillation was observed where the condensate and the thermal cloud oscillated out of phase - this mode has analogies to second sound [29].

The discussion of sound demonstrates that atomic condensates and liquid helium are in many respects complementary. Properties which were difficult to measure in liquid helium were easy in Bose condensed gases, and vice versa. The early observation of second sound in superfluid $^4$He was dramatic evidence for the presence of two fluids and played a major role in developing the theory of superfluidity. In contrast, in the trapped Bose gases, a clear signature of second sound has yet to be observed. However, the coexistence of the normal and the superfluid components was directly observed by imaging the cloud, either trapped or in ballistic expansion. Other examples are superfluidity and vortices. Their observations in liquid helium were clear evidence for the presence of a macroscopic phase. In the gaseous systems, the study of vortices and superfluid flow is more difficult, partially due to the mesoscopic size of the system. However, a macroscopic phase was directly observed in “matter wave” interference experiments [30–32].

4. Light scattering from a Bose-Einstein condensates

In the early ‘90s, before Bose-Einstein condensation was realized in atomic gases, there were lively debates about what a condensate would look like. Some researchers thought it would absorb all the light and would therefore be “pitch black”, some predicted it would be “transparent” (due to superradiant line-broadening [33]), others predicted that it would reflect the light due to polaritons [34] and be “shiny” like a mirror.

All the observations of Bose condensates have employed scattering or absorption of laser light. Until recently, the observations have been consistent with the assumption that a Bose condensate is a cold dilute cloud of atoms that scatters light as ordinary atoms do. On resonance, the condensate strongly absorbs the light, giving rise to the well-known “shadow pictures” of expanding condensates where the condensate appears black. For off-resonant light, the absorption can be made negligibly small, and the condensate acts as a dispersive medium bending the light like a glass sphere. This regime has been used for non-destructive in-situ imaging of Bose-Einstein condensates (see Fig. 1).

Our group has recently looked more closely at how coherent atoms interact with coherent light. Light scattering imparts momentum to the condensate and creates an excitation (Fig. 3). Consequently, the coherence and collective nature of excitations in the condensate can strongly affect the optical properties. As we discuss here, the use of light scattering to characterize atomic Bose condensates is analogous to the use of neutron scattering in the case of superfluid helium [22,35].

![Diagram of light scattering from a Bose-Einstein condensate](image-url)
Since the light scattered from a sample containing only $10^7$ atoms is hard to detect when it is distributed over the full solid angle, we used a second laser beam to stimulate the scattering of light with a frequency and direction, which was predetermined by the laser beam rather than post-determined by analyzing scattered light (Fig. 3). This scheme, which we call Bragg spectroscopy, establishes a high-resolution spectroscopic tool for Bose-Einstein condensates which is sensitive to the momentum distribution of the trapped condensate as well as the effects of interactions [36]. We studied Bragg scattering in two regimes differing by the amount of momentum transfer.

Bogoliubov theory predicts that for a momentum transfer which is smaller than the speed of sound (times the atomic mass) phonons are excited, whereas for larger momentum transfer, the excitations are free-particle like (Fig. 4). In the regime of large momentum transfer, the impulse approximation is valid, and the resonance shows a Doppler broadening due to the zero-point motion of the condensate, i.e. it can be used to measure the momentum distribution of the condensates as pursued for superfluid $^4$He [37,35]. More generally, Bragg spectroscopy can be used to determine the dynamic structure factor $S(q, \nu)$ over a wide range of frequencies $\nu$ and momentum transfers $q$ [38].

Bragg spectroscopy was realized by exposing the condensate to two off-resonant laser beams with a frequency difference $\nu$. The intersecting beams formed a moving interference pattern from which atoms could scatter when the Bragg condition was fulfilled (i.e. energy and momentum were conserved). The momentum transfer $q$ is given by $q = 2\hbar k \sin(\theta/2)$, where $\theta$ is the angle between the two laser beams with wave vector $k$. Figures 5 and 6 summarize the results for large and small scattering angles, probing both the phonon and free-particle regime. In the regime of low momentum transfer, light scattering was observed to be dramatically reduced (Fig. 6). In this regime, where atoms cannot absorb momentum “individually” but only collectively, the suppression arises from destructive interference of two excitation paths.

The suppression provides dramatic evidence for the presence of correlated momentum excitations in the many-body condensate wavefunction. A similar suppression would occur when a sufficiently dense condensate scatters light spontaneously—turning a “pitch-black” condensate transparent!

A condensate which reflected the incident light was encountered when it was illuminated with a single intense laser beam [41]. When a condensate has scattered a photon, an imprint is left in the form of long-lived excitations. These excitations form a periodic density modulation which diffracts light into the same direction as the first scattered photon. The more photons have been scattered into a certain direction, the larger is the density modulation left behind and the larger the increase of the scattering rate into this direction. This self-acceleration of scattering can be described as bosonic stimulation of the scattering by the population of the final (quasi-particle) state (see Fig. 3).

The gain for this process is highest when the light is scattered along the long axis of the cylindrically shaped condensate and leads to the generation of directed beams of atoms (Fig. 7). This is accompanied by directed emission of light—a new form of superradiance where a density modulation
5. Spinor Bose-Einstein condensates

In a magnetic trap, the atomic spin adiabatically follows the direction of the magnetic field. Thus, although alkali atoms have internal spin, their Bose-Einstein condensates are described by a scalar or-

spontaneously develops which makes the condensate “reflect” light like a mirror.

Fig. 5. Measuring the momentum distribution of a condensate [36]. A condensate was exposed to two counterpropagating laser beams. Atoms absorbed a photon from one beam and were stimulated to re-emit it by the other beam, resulting in the transfer of recoil momentum to the atoms, as observed in ballistic expansion using absorption imaging after 20 ms time-of-flight (upper part). The number of Bragg scattered atoms showed a narrow resonance when the difference frequency between the two laser beams was varied (upper and middle part). The width of the resonance is caused by Doppler broadening and is therefore proportional to the condensate’s momentum uncertainty $\Delta p$. It was determined for various sizes $\Delta x$ of the condensate. The agreement with the Heisenberg limit $\Delta p \approx \hbar/\Delta x$ proves that the Doppler width of the resonance is only due to the zero-point motion of the condensate, or equivalently, that the coherence length of the condensate is equal to its physical size. This demonstrates that a condensate is one “coherent matter wave”! An analogous measurement in the time domain has been done by W.D. Phillips’ group in Gaithersburg [39].

Fig. 6. (a) Static structure factor $S(q)$ and (b) shift of the line center from the free-particle resonance. $S(q)$ is the ratio of the line strength at a given chemical potential $\mu$ to that observed for free particles. As the density and $\mu$ increase, the structure factor is reduced, and the Bragg resonance is shifted upward in frequency. Solid lines are predictions of a local-density approximation for light scattering by 14 degrees. The dotted line indicates a mean-field shift of $4\mu/7\hbar$ as measured in the free-particle regime using a scattering angle of 180 degrees. Figure taken from Ref. [40].

Fig. 7. Superradiance and matter-wave amplification in a Bose-Einstein condensate [41]. The figure shows the velocity distribution of the atoms after a condensate (highest peak at the back of each image) was illuminated by laser light. Normal light scattering (rear image) is random, and the velocity distribution was smeared out in the direction of the incident light. In contrast, collective “superradiant” scattering created several highly directional “atom laser” beams (front image). The images are absorption images of a cloud which expanded ballistically after the light scattering. The two horizontal axes represent two velocity components and the vertical axis is the column density of the observed atoms. The closest spacing between the peaks is $\sqrt{2}$ times the single-photon recoil velocity.


...der parameter similar to the spinless superfluid $^4$He. One exception is the two-component condensate which was discovered by the Boulder group, when they trapped atoms in both the upper and lower hyperfine states of $^{87}$Rb [42]. This observation was surprising because a large rate of inelastic collisions had been predicted for this system. The suppression of these spinflip collisions turned out to come from a fortuitous equality in the scattering lengths in the two hyperfine states.

A general method for creating multi-component condensates is to employ an optical trap that can confine condensates with arbitrary orientations of the spin thus liberating the spin as a new degree of freedom. Our group used an optical trap to study condensates with arbitrary population in the three orientations $m = 1, 0, -1$ of the ground state of sodium which has a total spin $F = 1$ [43,44]. These condensates have a three-component vectorial order parameter. A variety of new phenomena have been predicted for such spinor condensates such as spin textures, spin waves, and the coupling between atomic spin and superfluid flow [45–47]. New phenomena cannot occur in condensates with a single component order parameter such as in $^4$He and resemble more the complex features of the superfluid phases of $^3$He.

If the components are not coupled (i.e. transformed into each other), they can be regarded as multi-species condensates ("condensate alloys"). Both the group in Boulder and our group have studied the dynamics of the phase-separation of these components [48,49]. We observed long-lived metastable structures which could tunnel through each other and reach the equilibrium configuration [50]. By selecting two of the three states of the $F = 1$ spinor condensates, we could realize two-component condensates which were either miscible or immiscible [44]. Multi-component condensates are promising systems for the study of interpenetrating superfluids, a long-standing goal since the early attempts in 1953 using $^4$He-$^6$He mixtures [51]. New phenomena arise when the three components are coupled by spinflip collisions, as displayed in Fig. 8.

6. Evidence for a critical velocity in a BEC

The existence of a macroscopic order parameter implies superfluidity of a gaseous condensate. Observing frictionless flow is a challenge given the small size of the system and its metastability. We have taken a step towards this goal by studying dissipation when an object was moved through the fluid [52]. This is in direct analogy with the well-known argument by Landau [25] and the vibrating wire experiments in superfluid helium [53]. Instead of a massive macroscopic object we used a blue detuned laser beam which repelled atoms from its focus to create a moving boundary condition.

The beam created a “hole” with a diameter of 13 µm which was scanned back and forth within the condensate which was cigar-shaped with Thomas-Fermi diameters of 45 and 150 µm in the radial and...
axial directions, respectively. After exposing the condensate to the scanning laser beam for about one second, the final temperature was determined. As a function of the velocity of the scanning beam, we could distinguish two regimes of heating separated by a critical velocity. For low velocities, no dissipation was observed, the condensate appeared immune to the presence of the scanning laser beam. For higher velocities, the heating increased, until at a velocity of about 6 mm/s the condensate was almost completely depleted after the stirring. The cross-over between these two regimes was quite pronounced and occurred at a velocity of about 1.6 mm/s which was a factor of four smaller than the speed of sound at the peak density of the condensate (Fig. 9).

These observations are in qualitative agreement with numerical calculations based on the nonlinear Schrödinger equation which predict the onset of vortex nucleation at such subsonic velocities [54–56]. Because of surface effects and the non-zero temperature, we expect dissipation even at low velocities and a smooth crossover between low and high dissipation. More precise measurements of the heating should allow us to study these finite-size and finite-temperature effects.

7. A new window into the quantum world

The direct observations of the condensate’s density distribution can be regarded as a direct visualization of the magnitude of the macroscopic wavefunction. The time evolution of the squared wavefunction of a single condensate has even been recorded non-destructively in real time [21,24]. A wavefunction is a probabilistic description of a system in the sense that it determines the distribution of measurements if many identical wavefunctions are repeatedly probed. In BEC, one simultaneously realizes millions of identical copies of the same wavefunction, and thus the wavefunction can be accurately determined while affecting only a small fraction of the condensed atoms by the measurement process. On the other hand, we have already observed quantum correlations which go beyond the simple single-particle picture [40].

Questions that have been triggered by Bose-Einstein condensation include the comparison of different statistical ensembles (microcanonical, canonical etc.) which agree in the thermodynamic limit, but not for small Bose-Einstein condensates [57–59]. The creation of a relative phase between two condensates could be discussed both in the framework of spontaneous symmetry breaking and of quantum measurement theory, and has lead to new insight [60,61]. Another question is under what conditions is it possible to have an absolute phase reference for condensates [62–64].

The rapid pace of developments in atomic BEC during the last few years has taken the community by surprise. After decades of an elusive search nobody expected that condensates would be so robust and relatively easy to manipulate. Also, nobody imagined that such a simple system would pose so many challenges, not only to experimentalists, but also to our fundamental understanding of physics. The list of future challenges is long and includes the exploration of superfluidity, vortices, and second sound in Bose gases, the study of quantum-degenerate molecules and Fermi gases, the development of practical “high-power” atom lasers, and
their application in atom optics and precision measurements.

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References


