EXPERIMENTAL STUDIES OF BOSE–EINSTEIN CONDENSATION

Since first being produced four years ago, Bose–Einstein condensates of dilute gases have provided a rich playground for exploring atomic, quantum, and many-body physics.

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The possibility of creating optical fields with many photons in a single mode of a resonator was realized with the creation of the laser in 1960. The possibility of creating a matter-wave field with many atoms in a single mode of an atom trap—the atomic equivalent of an optical resonator—was realized with the achievement of Bose–Einstein condensation (BEC) in 1995.

Because of the wealth of new phenomena displayed by the condensates, and the precision and flexibility with which they can be manipulated (see figure 1), interest in them has grown explosively in the communities of atomic physics, quantum optics, and many-body physics. At least 20 groups have created condensates, and the publication rate on BEC has soared following the discovery of the gaseous condensates in 1995 (see figure 2).

Although atomic condensates and laser light share many properties, they also differ fundamentally: Atoms readily interact, photons do not. As a result, the atomic condensates constitute a novel class of many-body systems that provide a new laboratory for many-body physics. They have already yielded discoveries such as stable condensates with attractive interactions, multicomponent condensates, and Feshbach resonances, and they have led to advances in many-body theory. Furthermore, because atoms interact, atom optics is inherently nonlinear optics. Consequently, nonlinear effects, such as four-wave mixing, that were first achieved with light only with difficulty, occur almost automatically with coherent matter waves.

In this article, I sketch the underlying concepts of atomic BEC and describe some of the recent experimental advances.[1] The theoretical aspects of BEC are discussed in the accompanying article by Keith Burnett, Mark Edwards, and Charles Clark (page 37) and in a recent review.[2]

Einstein's prediction

When a gas of bosonic atoms (atoms with integer spin—see box 1 on page 32) is cooled below a critical temperature, a large fraction of the atoms condenses in the lowest quantum state. This phenomenon was first predicted by Albert Einstein in 1925 and is a consequence of quantum statistics.[3] (See box 2 on page 32.) Atoms of mass m at temperature T can be regarded as quantum mechanical wavepackets whose extent is on the order of their thermal de Broglie wavelength $\lambda_{\rm dB} = (2\pi\hbar^2/mk_{\rm B}T)^{1/2}$, which represents the position uncertainty associated with the thermal momentum distribution. When atoms are cooled to the point where $\lambda_{\rm dB}$ is comparable to the interatomic separation, the atomic wavepackets overlap and the indistinguishability of particles becomes important. At this temperature, bosonic atoms undergo a quantum mechanical phase transition and form a Bose–Einstein condensate, a coherent cloud of atoms all occupying the same quantum mechanical state. The transition temperature and the peak atomic density ρ are related: $\rho\lambda_{\rm dB}^3 \approx 2.612$.

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How to make a Bose–Einstein condensate

Creating BEC is simple in principle: Cool a gas until the thermal de Broglie wavelength is roughly the distance between atoms. However, in almost all cases, the BEC phase transition is preempted by the more familiar phase transitions that lead to liquids or solids. Interactions then localize the atoms and prevent BEC—the only exception is liquid helium. BEC in atomic gases can be achieved only by using extremely dilute gases so that the formation time for molecules and clusters by three-body collisions is slowed to seconds or minutes. The thermalization time by elastic binary collisions is typically 10 ms, so that BEC can be achieved in what is essentially a metastable gaseous phase. The density ρ at the transition temperature is typically 10^{14} cm^{-3} (which corresponds to the density of a room-temperature gas at a pressure of 10^{-2} mbar), and the transition occurs at submicrokelvin temperatures.

Techniques for cooling to such record low temperatures were developed in the 1980s: Several laser cooling techniques[4] are used to precool the gas, which is then confined in a magnetic trap. The 1997 Nobel Prize in Physics was awarded for the development of the laser cooling and trapping methods that are essential for atomic BEC (see PHYSICS TODAY, December 1997, page 17). Further cooling is provided by forced evaporative cooling—first demonstrated by the group of Tom Greytak and Dan Kleppner at MIT—in which the depth of the trap is reduced, allowing the most energetic atoms to escape while the remaining atoms rethermalize at progressively lower temperatures.[5] In the early 1990s, work done primarily by a team led by Eric Cornell and Carl Wieman at JILA in Boulder, Colorado, and by my group in collaboration with David Pritchard's group at MIT, successfully combined laser cooling, which works best at low atomic density, and evaporative cooling, which works best at high density. This development required new techniques for laser cooling (the so-called dark traps), for magnetic trapping (new trap configurations), and for evaporative cooling (the use of RF-induced spin flips to selectively remove atoms from a magnetic trap).

Although BEC experiments are conceptually simple, they pose major technical challenges. BEC was first demonstrated by the Boulder group using rubidium (June 1995), by my group using sodium (September 1995), and

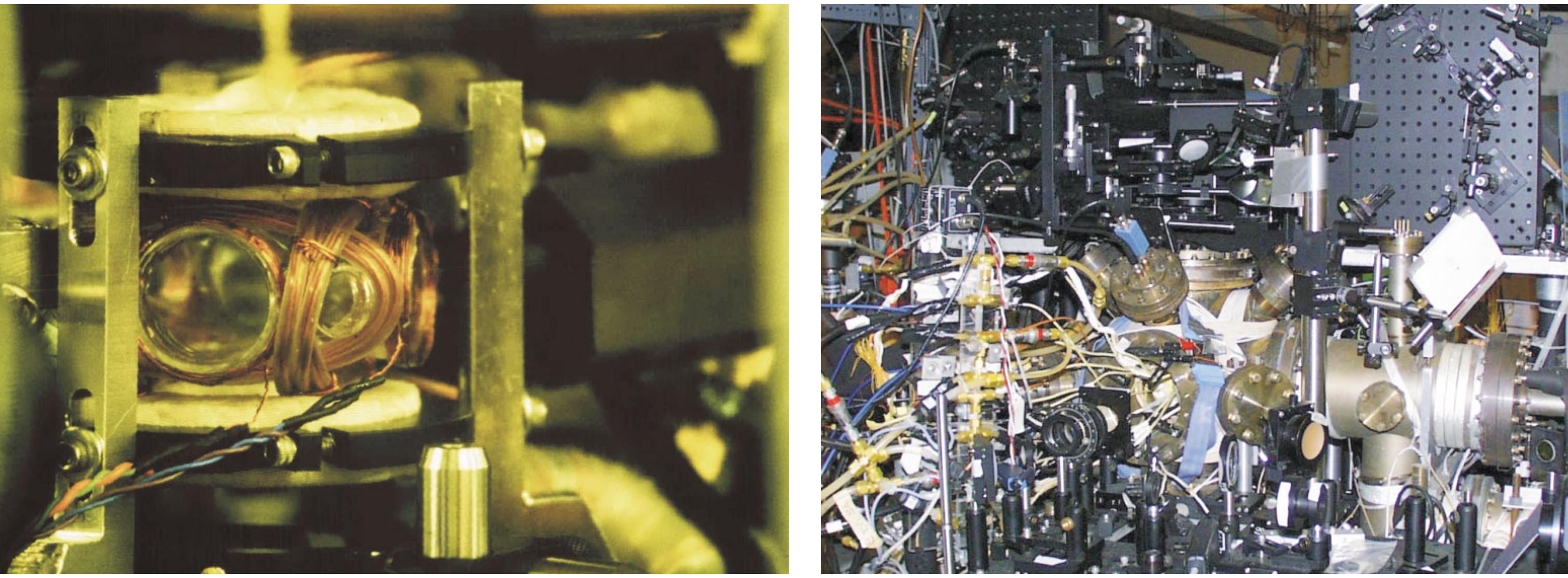


FIGURE 1. EXPERIMENTAL SETUPS for studying Bose–Einstein condensates. The left-hand photo shows the ultrahigh vacuum glass cell, with a window diameter of 2.5 cm, surrounded by the coils of the magnetic trap, used at JILA for rubidium condensates. The right-hand photo shows the central part of the vacuum chamber for my group's sodium condensates, surrounded by optics for laser cooling and optical probing. No cryogenic apparatus is necessary for either setup—the combination of magnetic trapping and ultrahigh vacuum provides sufficient insulation.

by the Rice University group under Randy Hulet using lithium (indirect evidence in July 1995).[6] However, the experiments are so complex that it took until 1997 for second-generation experiments to get on-line. Every new BEC experiment is still welcomed like a new child in the family (see the BEC home page[1]). The only new addition to the list of atomic species has been hydrogen, which was condensed by Greytak, Kleppner, and their collaborators, fulfilling a quest of more than two decades (see PHYSICS TODAY, October 1998, page 17).[7] Work in potassium, cesium, chromium, strontium, metastable neon, and helium is under way.

Most BEC experiments reach quantum degeneracy at temperatures between 500 nK and 2 μK, with densities between 10^{14} and 10^{15} cm^{-3}. The largest condensates in sodium have 20 million atoms and in hydrogen, 1 billion atoms. A cooling cycle takes between 10 seconds and several minutes. During this time, the temperature is reduced by a factor of a billion from room temperature or higher to the submicrokelvin regime. Depending on the magnetic trap, the shape of the condensate is approximately round with a diameter of 10 to 50 μm, or cigar-shaped with a diameter of about 15 μm and a length of 300 μm. Although the internal energy due to the repulsion between atoms[2] is between 10 and 100 nK, the kinetic energy due to the zero-point motion in the condensate can be less than 10 pK along the long axis in cigar-shaped condensates.

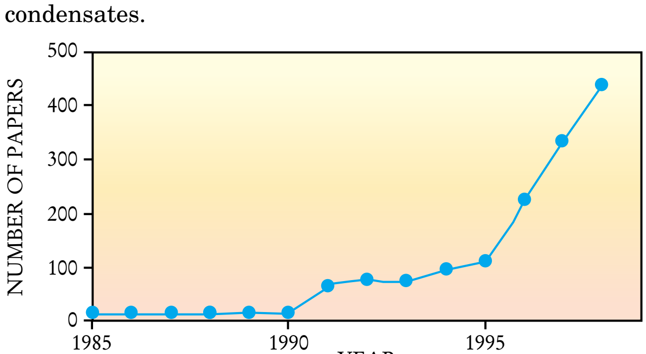


FIGURE 2. ANNUAL NUMBER of published papers that have the words "Bose" and "Einstein" in their title, abstract, or keywords, from 1985 through 1998. The data were obtained by searching the Institute for Scientific Information database.

The signature of reaching quantum degeneracy is dramatic. The sudden appearance of the condensate can be observed in ballistic expansion following a fast switching off of the trap. Using absorption imaging, the condensate shows up as a second component of the atom cloud that expands with a much lower velocity than the thermal component. The trapped condensate can also be monitored *in situ* by light scattering techniques, appearing as a dense core amidst the more diffuse thermal cloud. (The basic phenomenon of BEC in gases and its observation are described in PHYSICS TODAY, August 1995, page 17, and March 1996, page 18, and in reference 8.)

Atoms interact

Bose-condensed atoms are distinguished from photons in a laser by their interactions. The atomic condensates have turned out to be an unexpectedly valuable testing ground for the study of interacting many-body systems.[2] An attractive feature of BEC in dilute atomic gases is that it can be theoretically described from first principles. The theory of the weakly interacting Bose gas was developed in the late 1940s and 1950s and requires that binary collisions are much more frequent than three-body collisions. This condition is fulfilled when the separation between atoms, $\rho^{-1/3}$, is much larger than the effective range of the interatomic forces, characterized by the s-wave scattering length a. The scattering length is typically 1 to 5 nm for alkali atoms, so that $\rho a^3 \approx 10^{-6}$. The stability of large condensates requires repulsive interactions (positive a). For attractive interactions (negative a), the condensate is unstable against collapse above a certain size, as verified by Hulet and his colleagues. They also studied fluctuations of the atom number after the collapse.[9]

Recent experimental work illustrates the variety of physics that can be explored using Bose–Einstein condensates. (Unfortunately, the scope of this article does not

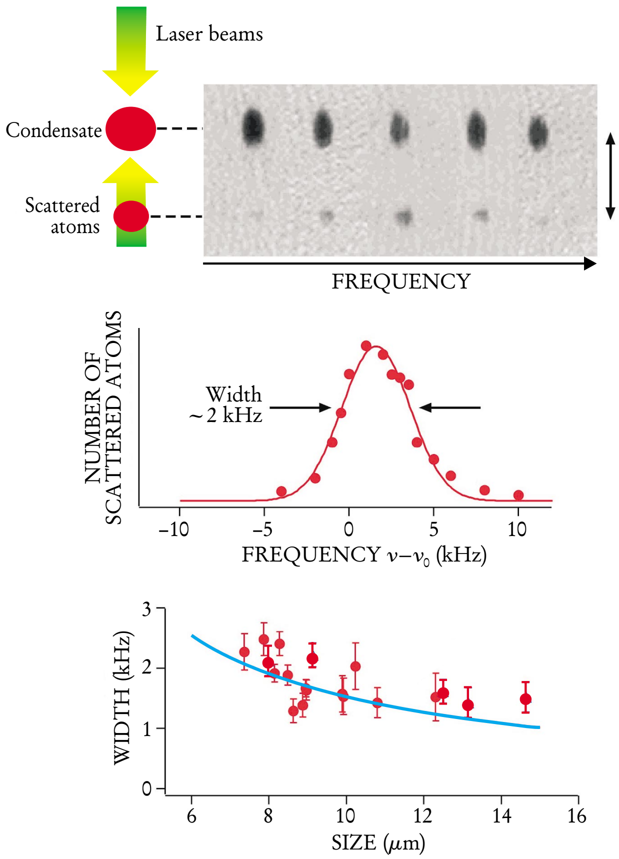


FIGURE 3. MEASURING THE COHERENCE LENGTH of a condensate.[16] When a condensate was exposed to two counterpropagating laser beams, some atoms absorbed a photon from one beam and were stimulated by the other beam to reemit it. The recoil momentum kicked these atoms out, as observed using absorption imaging after a 20 ms ballistic expansion (upper panel). The number of scattered atoms showed a narrow resonance when the difference frequency between the two laser beams was varied (upper and middle panels). The width of the resonance, caused by Doppler broadening and therefore proportional to the condensate's momentum uncertainty Δp, was determined for various sizes Δx of the condensate (lower panel). The agreement with the Heisenberg limit $\Delta p \approx \hbar/\Delta x$ (blue line) proves that the Doppler width of the resonance was only due to the zero-point motion of the condensate, or equivalently, that the coherence length of the condensate was equal to its physical size. This result demonstrates that a condensate is one coherent matter wave!

allow me to do full justice to the rapidly growing field, but comprehensive reviews are available.[10]) 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 the photons in a laser. Experiments in this area are preferentially done at low densities. Here, Bose–Einstein condensates serve as an intense source of ultracold coherent atoms for experiments in atom optics, for use in precision studies, or for explorations of basic aspects of quantum mechanics. The second area could be labeled "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.

Atom lasers and coherence

In an ideal gas, Bose-condensed atoms would all occupy the same single-particle ground state wavefunction. This picture is largely valid even when weak interactions are included, with corrections (due to admixtures of other configurations) of typically 1% or less for the alkali condensates. In contrast, for liquid helium this correction—called quantum depletion—is about 90%. Thus, even for the interacting gases, the atoms can all be regarded as having the same single-particle wavefunction with 99% accuracy. Consequently, gaseous Bose–Einstein condensates can serve as sources of coherent atomic beams—so-called atom lasers.

The coherence of the condensate[11] was demonstrated in 1997 when two condensates in a double-well potential were released from the trap and allowed to expand. They displayed a high-contrast interference pattern in their overlap region (see PHYSICS TODAY, March 1997, page 17). When Mark Kasevich's group at Yale University trapped a condensate in a multiwell optical potential, they observed interference between the atoms tunneling out of different wells. The temporal oscillations seen in the interference pattern were related to Josephson oscillations. Coherence

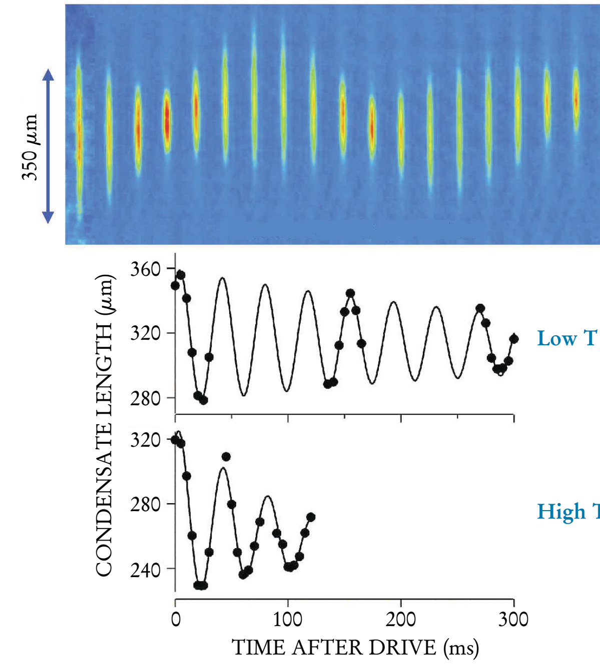
Box 1. Composite bosons

Atoms and molecules are composite particles. They are bosonic if they have integer spin or, equivalently, if the total number of electrons, protons, and neutrons they contain is even; they are fermionic if they have half-integer spin, or an odd total number of electrons, protons, and neutrons. Under what conditions can we regard these composite particles as pointlike? The composite nature manifests itself in internal excitations. If the energy necessary for an internal excitation is much larger than k_BT, then the internal degrees of freedom are frozen out and inconsequential for describing the thermodynamics at temperature T. The first electronically excited state of a system of size d has an energy of $\hbar^2/m_e d^2$, where m_e is the electron mass. Since the range a of interactions is usually much larger than d, the condition for a gas to be dilute ($\rho a^3 \ll 1$) already guarantees that, in the condensate, k_BT is much smaller than the internal excitation energies. Therefore, electronic excitations cannot affect the properties of a dilute Bose condensate. However, the composite boson can have spin structure, which can result in several hyperfine ground states and lead to multicomponent condensates.

Box 2. Can photons Bose condense?

Due to the laws of quantum statistics, a macroscopic population of bosonic (integer spin) atoms in the ground state of a system is achieved merely by lowering the temperature. In contrast, in an optical laser a nonequilibrium process is necessary to generate a macroscopic population of photons in a single mode of the electromagnetic field. The difference is that the number of atoms is conserved, whereas that of photons is not. For bosonic atoms below a certain temperature, the state of highest entropy includes a macroscopic population of the ground state. In contrast, when one cools a blackbody cavity, the cavity empties. Instead of Bose condensing into the ground state of the cavity, the photons are absorbed by the walls, and that increases the total entropy. However, if a photon gas were to thermalize with the number of photons being conserved—for instance, by Compton scattering with a thermal electron gas—it could, in principle, form a Bose condensate of photons. Achieving Bose–Einstein condensation requires a thermalization time that is shorter than the storage time of the particles—a principle that applies both to photons and atoms.

FIGURE 4. COLLECTIVE OSCILLATIONS of a Bose–Einstein condensate. The oscillations were observed by first modulating the magnetic trapping potential to excite the condensate, and then imaging the condensate nonperturbatively using phase-contrast imaging. The top panel shows images taken 5 ms apart. The periodic changes in length and width are quadrupolar shape oscillations, the lowest-lying "phonon" excitation of the system. The damping rate of this oscillation increased strongly at higher temperatures.[17]



in multicomponent condensates was demonstrated by the Boulder group. A recent spectroscopic measurement of the coherence length of a condensate is illustrated in figure 3. An analogous measurement in the time domain has been done by William Phillips and his coworkers at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland.

Several techniques have been exploited for coherently expelling condensed atoms from a trap. My group created an output coupler in 1997 by using pulsed RF radiation to flip the spins of a fraction of the condensed atoms into an untrapped state that fell downward due to gravity. Since the atoms were coherent, the system constituted a pulsed atom laser. Ted Hänsch and his colleagues at the University of Munich and the Max Planck Institute for Quantum Optics in Garching exposed a magnetically shielded condensate to continuous RF radiation, thereby obtaining a continuous-wave output coupler. Phillips and his coworkers replaced the RF transition with an optical Raman transition. The photon recoil pushed the atoms out of the trap, realizing a directional output coupler (PHYSICS TODAY, April 1999, page 17). Further experiments on output coupling have recently been performed by Andrew Wilson's group at the University of Otago in New Zealand.

The gain mechanism of an atom laser is analogous to that in the optical laser: The coherent matter wave stimulates other atoms to scatter into the same mode, thereby amplifying it. Such bosonic stimulation has been observed in the formation of the condensate at MIT, during four-wave mixing experiments at Gaithersburg, and, most dramatically, in the buildup of "superradiant" pulses of matter waves.

Applications for atom lasers

What will atom lasers be used for? The Gaithersburg group has used the condensate as a superior atom source with its high brightness, small momentum spread, and excellent initial spatial localization. The researchers' experiments include several studies of diffraction of atoms by light, an important element in atom interferometers. In the optical domain, the laser is crucial for nonlinear optics. Similarly, atom lasers are crucial for nonlinear atom optics. In contrast to photons, however, atoms have no need for a nonlinear medium—their interactions provide the nonlinearity. A beautiful example is the recent Gaithersburg experiment, in which three condensates collided and formed a fourth condensate by four-wave mixing (see PHYSICS TODAY, September 1999, page 17).

Condensates can be highly nonlinear media, not only for matter waves but also for light. This behavior was dramatically demonstrated recently by Lene Hau and her collaborators at the Rowland Institute in Cambridge, Massachusetts, when they slowed the speed of light pulses to 17 m/s using the condensate as a dense cold medium (see PHYSICS TODAY, July 1999, page 17). Ultimately, atom lasers may replace conventional atomic beams in applications such as precision measurements of fundamental constants, tests of fundamental symmetries, atom optics (in particular, atom interferometry, and atom holography), and precise deposition of atoms.

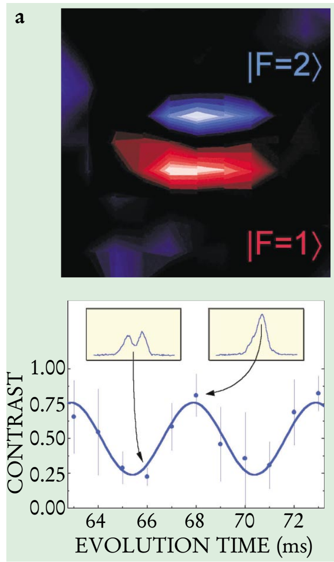
Squeezing and poking collective excitations

Let us turn now to a discussion of the condensate as a many-body system. How do physicists characterize a new form of matter? They shake it, poke it, shine light on it, and see what happens! In some of the earliest studies done in 1996 at MIT and JILA, condensates were excited by modulating the magnetic trapping potential.[10] The condensate reacted like a piece of jelly shaking at its lowest excitation frequencies—typically around 100 Hz, on the order of the trapping frequency. These shape oscillations corresponded to standing sound waves with a wavelength comparable to the size of the system. For pure condensates, their frequencies agreed well with theoretical predictions for a Bose gas at zero temperature, with an accuracy of a few parts per thousand. At finite temperatures, frequency shifts and increased damping rates were observed, which were not accounted for by available theories. As a result, during the last few years, many attempts have been made to advance many-body theory to describe Bose–Einstein condensates at finite temperature in an inhomogeneous trapping potential.[2]

Bulk properties of a condensate can be studied by exciting sound with wavelengths smaller than the dimension of the sample. A first step in this direction was our observation of propagating density perturbations, which traveled along the long axis of an elongated condensate with a speed of about 1 cm/s. This measurement of the speed of sound finally confirmed predictions made by Nikolai Bogoliubov in 1948 and Kerson Huang, T. D. Lee, and C. N. Yang in the 1950s.

We recently achieved even shorter wavelength excitations using optical standing waves with a wavelength of 2.5 μm to modulate the condensate's density, thereby optically "imprinting" phonons into the quantum gas.[12] This experiment determined the dynamic structure factor for a gaseous condensate, which characterizes the spectrum of collective excitations. It is a first cousin to the study of collective excitations of liquid helium by neutron scattering, in which the momentum and energy of the scattered neutrons are analyzed. The analogous light scattering technique with a single laser beam would not have provided a detectable signal, given the small size of the Bose condensed samples. Therefore, scattering in a preselected direction was strongly enhanced by stimulating it with a second laser beam that, together with the first, formed the optical standing wave.

These examples demonstrate that atomic condensates and liquid helium are in many respects complementary. Properties that were difficult to measure in liquid helium were easy in Bose condensed gases, and vice versa. For example, the very first observations of BEC showed the appearance of a condensate with a narrow velocity distribution, and Cornell and Wieman's team and my group could immediately measure the condensate fraction as a function of temperature. Related studies done by neutron scattering from liquid helium took 20 years to reliably yield a condensate peak. On the other hand, superfluidity provided a spectacular first indication that liquid helium was a quantum liquid, whereas superfluidity in an atomic condensate has not yet been directly observed (see PHYSICS TODAY, November 1999, page 17).



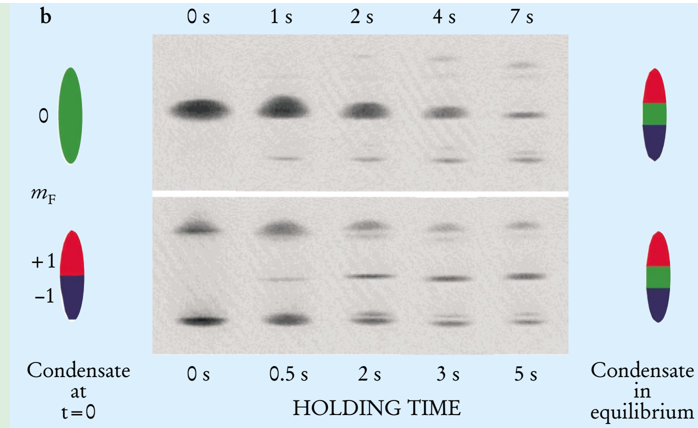


FIGURE 5. COUPLED MULTICOMPONENT CONDENSATES. **(a)** In an experiment at JILA, a two-component condensate was created by splitting a single condensate in a phase-coherent way with RF radiation. The two components, in the upper and lower hyperfine states of rubidium-87, can be distinguished in a phase-contrast image (upper panel), which displays the differential density of the components. The inserts in the lower panel show vertical profiles through absorption images after the double condensate was exposed to an RF pulse. In the overlap region, there is either a dip (destructive interference) or a peak (constructive interference), depending on the relative phase of the two condensates. Remarkably, even after phase separation and some sloshing, the relative phase was reproducible and oscillated periodically in time.[11] **(b)** In experiments at MIT, an antiferromagnetic spin-flip interaction coupled the different components of a condensate and drove them into an equilibrium domain structure. Condensates with different orientations $m = -1, 0, +1$ of the total spin $F = 1$ were confined in an optical trap and analyzed after a variable holding time. During the ballistic expansion, a magnetic field gradient acted as a Stern–Gerlach filter and separated the components with different spin orientation, as indicated by the arrows. The equilibrium spin domain structure that developed from a pure $m = 0$ state (top) was the same as from an equal mixture of $m = +1$ and -1 states (bottom). The bimodal density distribution of the +1 and −1 components reveals their miscibility.[14]

What does a condensate look like?

In the early 1990s, before BEC was achieved 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 linebroadening; some predicted that it would reflect the light, because of polaritons, 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 (as in figure 3). 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 nondestructive *in situ* imaging of Bose–Einstein condensates (see figure 4).

It is only in this year that we, in collaboration with Pritchard's group, have looked more closely at how coherent atoms interact with coherent light. Light scattering imparts momentum to the condensate and creates an excitation. Consequently, the coherence and collective nature of excitations in the condensate can strongly affect the optical properties. When the recoil velocity due to the light scattering was less than the speed of sound in the condensate, we observed dramatically reduced light scattering.[12] In this regime, in which atoms cannot absorb momentum individually but only collectively, the suppression arises from two excitation pathways that interfere destructively. This suppression provides dramatic evidence for the presence of correlated momentum excitations in the many-body condensate wavefunction. For a sufficiently dense condensate, this effect can make a pitch-black condensate become transparent.

When higher laser intensities were used, it was discovered that the light was not scattered randomly, but emitted along the axial direction of the elongated condensate. This effect, which is due to self-amplification of a density modulation (in essence a grating formed by matter waves), represents a new form of superradiance. As a result, the condensate reflects light like a mirror (see PHYSICS TODAY, September 1999, page 17).

Multicomponent condensates

The atoms used so far for BEC have been trapped magnetically, which requires that they have a nonvanishing electron spin. As a result, there is spin structure in the atomic ground state, making it possible to create multicomponent condensates (also called spinor condensates). A two-component condensate was discovered by the JILA researchers[13] when they trapped atoms in both the upper and lower hyperfine states of ^{87}Rb. This observation was surprising because a large rate of inelastic collisions had been predicted for the system. The suppression of these spin-flip 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. Such a trap has been used to study condensates with arbitrary population in the three orientations $m = 1$, 0, and -1 of the $F = 1$ hyperfine ground state of sodium.[14]

These condensates have two- or three-component order parameters, which have SU(2) or vectorial symmetry.[15] A variety of new phenomena have been predicted for these multicomponent condensates, including spin textures, spin waves, and coupling between atomic spin and superfluid flow. Such phenomena cannot occur in condensates with a single-component, complex order parameter such as helium-4.

If the components are not coupled (that is, if they are not transformed into each other), they can be regarded as multispecies condensates, or "condensate alloys." Cornell and Wieman's team and my group have studied the dynamics of the phase separation of these components. We observed long-lived metastable structures that could tunnel through each other and reach the equilibrium configuration. By selecting two of the three states of the $F = 1$ spinor condensates, we could produce two-component condensates that were either miscible or immiscible. Multicomponent 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.

New phenomena arise when the components are coupled, as displayed in figure 5. Recently, the JILA group has discovered how to manipulate two-component condensates in a phase-coherent way. The researchers observed twisting and unwinding of the SU(2) order parameter by driving the system with strong RF fields (see PHYSICS TODAY, November 1999, page 17).

A new window on the quantum world

The direct observation 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 wavefunction of a single condensate has even been recorded nondestructively in real time (see, for example, figure 4). 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 produces millions of identical copies of the same wavefunction, and thus the wavefunction can be accurately determined while only a small fraction of the condensed atoms are affected by the measurement process. On the other hand, quantum correlations that go beyond the simple single-particle picture have already been observed.[12]

Questions that have been triggered by BEC include the comparison of different statistical ensembles (microcanonical, canonical, and so forth) that agree in the thermodynamic limit, but not for small Bose–Einstein condensates. The creation of a relative phase between two condensates could be discussed in the framework of both spontaneous symmetry breaking and quantum measurement theory, and has led to new insight.[2] Another question that has been addressed by Tony Leggett (University of Illinois at Urbana–Champaign) and others is, Under what conditions is it possible to have an absolute phase reference for condensates?

The rapid pace of developments in atomic BEC during the last few years has taken the physics 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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