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Bose-Einstein condensation

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ARTICLE

The attainment of Bose-Einstein condensation (BEC) in a weakly interacting atomic gas has opened up a new frontier in physics. Many scientists working in physics or related fields now consider it manifest destiny that BEC will be part of many new scientific discoveries and, perhaps, new technologies. Why is this? What makes the condensate so interesting? What makes it potentially useful? First, some background.

In quantum mechanics, elementary particles of the same type are considered identical. For example, an electron in an atom could be replaced by another electron and the atom would behave in exactly the same way. Nature has taken particular advantage of this, allowing only two types of elementary particles: bosons and fermions. They differ fundamentally in how a collection of identical particles interact. Identical fermions cannot occupy the same quantum state (only one per state!). Identical bosons can occupy the same quantum state. The statistics of identical particles (how they act in groups) has profound affects. For example, the rich and complex structure of the periodic table arises from the principle that only one electron can occupy each quantum state. The spin and the statistics of particles are closely connected: (fermions) bosons have (half-)integer spin. (Spin is an internal angular momentum measured in units of Planck's constant.)

Composite particles, such as atoms, also behave as bosons or fermions. Depending on the number of electrons, protons and neutrons, an atom can have integer or half-integer total spin and, therefore, be a boson or fermion. We most commonly encounter atoms in situations where their fermionic or bosonic nature is not manifested. This is because the atoms are either at too high an energy or are too rarefied for quantum effects to be important. In solids, the atoms interact strongly. As a result, they are localized and don't compete for the same space so indistinguishability plays a minor role. The only material that does not become solid at low temperatures is liquid helium. When liquid helium is cooled below 2.2 K, a Bose condensate begins to form in the liquid. At these low temperatures, liquid helium behaves as a superfluid having, among other strange properties, zero viscosity.

When gaseous bosonic atoms are cold enough (so that they have a long quantum wavelength) and dense enough (so that the spacing between the particles is on the order of the wavelength), quantum effects become important and the gas may undergo a phase transition into the Bose condensed state. This must be done in a density regime low enough so that the gas does not nucleate and form a solid. BEC was achieved with three elements: rubidium, sodium, and lithium. Although all elements (except for beryllium) have stable bosonic isotopes, the alkali atoms were used because they can be very efficiently laser-cooled. Laser cooling was the first step toward attaining BEC in these atoms.

Laser cooling works by scattering photons from moving atoms. Although the momentum of the photons is small, the alkali atoms can absorb and emit many times and therefore be quickly cooled. With the proper arrangement of laser beams, these atoms can be cooled to about 50 µK with a density of 5×10^{11} cm^{-3}, still far from the low temperatures and high densities needed for BEC. At this point, two other techniques are used: magnetic trapping and evaporative cooling. The atoms are trapped by creating a magnetic field minimum in free space using a simple arrangement of electromagnets. (Many atoms, including Rb, Na, and Li, are paramagnetic and can, therefore, be magnetically trapped.) Those atoms in the low field-seeking state (the magnetic moment anti-aligned with the magnetic field) can be confined in the trap. Any atom with energy above the depth of the trap can escape (evaporate). These escaping atoms necessarily have energies above the trap depth and are the hottest atoms in the gas. The atoms left in the trap cool slightly and sink deeper into the trap, thus increasing in number density. If the depth of the trap is lowered slowly, the hottest atoms are "forced" to evaporate and the sample cools continuously while its density increases. These are perfect conditions for achieving BEC! A "typical" condensate is shown in Fig. 1.

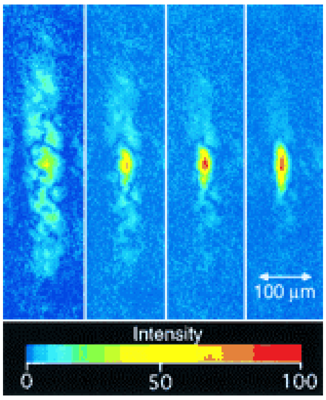

Fig. 1. Direct observation of BEC of magnetically trapped sodium atoms by dispersive light scattering. The clouds have condensate fractions that increase form close to 0% (left) to almost 100% (right). The dense core is the condensate, and the more diffuse cloud is the normal component. The signal for the normal component is rather weak and appears patchy due to interference with laser stray light (adapted from ref. 1).

Understanding the quantum fluid nature of the condensate should help us understand some of the properties of other quantum fluids (like liquid helium). Recent measurements of the thermal and fluid properties of the condensate suggest that it is similar to liquid helium but will also exhibit traits that are uniquely its own. Thus the properties of the gaseous Bose condensate are worthy of careful study.

Perhaps most simply, physicists find BEC intriguing because it is quantum mechanics brought to the human scale. The size of this wave function is much larger than the other quantum systems that we most often think of. The effect of cooling these atoms into the nK regime is to greatly amplify the spatial scale of quantum mechanics. Seeing first hand such a large wave function will, perhaps, give physicists a better intuitive feel for quantum mechanics. It may even make quantum mechanics understandable to acolytes of science, thus bringing an important part of our understanding of the world to a wider audience.

Atoms in the BEC state are all part of one macroscopic quantum wave function. Because of this, BEC is like a laser for atoms. Similar to the photons in a laser, all of the atoms in a condensate have exactly the same energy and spatial mode. The advantages that a laser brings to many applications are high intensity and phase coherence. It may be possible to realize similar gains for atoms. The realization of an "atom laser" (now used in the sense of BEC as a source of coherent atoms) would be a boon to the field of atom optics. Also, just about any experiment or technology currently using atomic beams would probably benefit from a higher intensity, coherent beam.

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ABBREVIATION

BEC, Bose-Einstein condensation.

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