Bose–Einstein Condensation

The dramatic effects of quantum mechanics are generally limited to the extremely small, to the atomic or subatomic scale. When materials become cold enough, however, quantum effects can be enormously enhanced and can extend across macroscopic distances. The best known examples of this occur in solids and liquids and are known as superconductivity and superfluidity, respectively. The analogous phenomenon in a gas is called Bose–Einstein condensation (BEC). Although the existence of BEC in a gas was predicted 70 years ago by Einstein, creating an experimental sample of the material has proved to be very difficult because it requires temperatures that are only a tiny fraction of a degree above absolute zero. Several groups have pursued this goal for many years, and it was finally achieved early in June, 1995. Two years earlier, scientists had achieved BEC in a short-lived cluster of electrons in a metal, which had a number of similarities to a gas.

According to the laws of quantum mechanics, the “fuzziness” associated with the uncertainty in the location of any particle becomes larger as the temperature of the particle is decreased. When a gas of identical atoms gets sufficiently cold and dense that the uncertainty in each atom’s location is as large as the average distance between the atoms, quantum mechanics can suddenly have a profound effect on the behavior of the entire sample of gas. If the atoms are “bosons,” which is to say if they have integer spin, they will suddenly have a strong preference for losing their individual identities and instead all occupying the same quantum mechanical state. This remarkable condensation of many atoms into a single quantum state is the Bose–Einstein phase transition.

Efforts to cool gases to the BEC transition began over 20 years ago, originally in specially prepared hydrogen atoms whose magnetic axes are lined up with each other. When traditional refrigerators and insulated containers proved to be inadequate, techniques were developed for holding gases of atoms in magnetic trapping fields and cooling them by allowing the warmer atoms to evaporate from the gas. More recently, atomic physicists have turned to laser-cooled gases of alkali atoms. Forces exerted by laser beams are used to confine atoms and to cool them to a few millionths of a degree Kelvin. This is still far from BEC. The final successful effort, at the Joint Institute for Laboratory Astrophysics (JILA) of the University of Colorado and the National Institute of Standards and Technology (NIST), Boulder, CO, combined both laser-cooling and evaporative cooling in a relatively simple apparatus to reach temperatures below 100 nanokelvin.

The hybrid of optical and evaporative cooling has also been used in several other labs around the country. Groups at Stanford and MIT have achieved combinations of density and temperature near that needed for the BEC transition in sodium, and a Rice University group has seen a signature for BEC in lithium-7. And in late 1995, an MIT group announced that they achieved Bose–Einstein condensation in a sodium gas comprised of approximately half a million atoms.

In the JILA experiment, a very low pressure, room-temperature vapor of rubidium-87 is collected and cooled by the optical forces exerted by six intersecting laser beams. The laser beams are then turned off and magnetic fields are turned on to hold the atoms. Each atom has a tiny magnetic-dipole moment, and the forces exerted by the magnetic fields on the atoms trap them in such a way that each atom is confined like a ball rolling back and forth in a bowl. The low-energy atoms remain near the bottom of this bowl-like “potential well” while the higher-energy atoms go further up the side of the well to the edge of the trap. These high-energy atoms are skimmed off the edge of the gas cloud, and, as the remaining atoms exchange energy by collisions, the sample becomes colder. Keeping the atoms tightly confined for long enough to realize sufficient evaporative cooling was made possible at JILA by an innovation in magnetic trapping called the time-averaged orbiting potential (TOP) trap.

A “snapshot” of the cloud of cold vapor is produced by illuminating it with a brief flash of laser light and capturing its image with a
video camera (see the figure on the cover of this book). The density and velocity distributions of the atoms in the cold cloud are obtained from the shape and brightness of the image. When the cloud is cooled below the BEC transition there is a sudden large increase in the number of atoms with nearly zero velocity. These sit at the bottom of the trap, as is expected for atoms occupying the lowest energy quantum state, and are dramatic evidence of the condensation. At the lowest temperatures the entire remaining sample (about 2000 atoms) is in the condensate. When the magnetic trap is turned off the condensate spreads out slowly in an elliptical pattern. The spreading agrees with the small amount of motion required by the uncertainty principle of quantum mechanics. This principle also explains the elliptical shape, which contrasts with the uniform spreading in all directions that is produced by a normal sample of atoms.

The gaseous Bose condensate shares many qualitative features with the exotic phenomena of superfluidity and superconductivity. It is far more amenable, however, to measurements of its properties and to the investigation of how these are related to the microscopic behavior of the atoms involved. Once these properties are better understood applications may follow. An aspect of Bose condensation that encourages such speculation is its close analogy to laser light. The identical photons in laser light are similar to the atoms in the Bose condensate in that there are a large number that occupy the same state. Just as the advent of the laser sparked many developments in optics, the availability of Bose-condensed atoms may have an analogous impact on the infant field of atom optics, with potential applications to nanofabrication and atom interferometry.

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