Helium Joins Family of Gaseous Bose–Einstein Condensates

> Now that researchers have observed the condensation of a gas of helium in its metastable state, helium is the first atom to form a Bose condensate in two phases.

Until 1995, Bose–Einstein condensation (BEC) could be found only in superfluid helium-4 and helium-3 and in the Cooper pairs of superconductors. Because these systems are strongly interacting, they display unique phenomena but also pose unique challenges to theory. Then, over a three-year period, condensation was achieved in gases of alkali atoms (rubidium, lithium, and sodium) and, most recently, hydrogen. (See PHYSICS TODAY, December 1999, page 30 and page 37.) These dilute gases interact only weakly, and are thus much easier to understand theoretically.

Now, two years after the last report of a new kind of atomic condensate, the oldest known Bose-condensing system, helium, is back in the spotlight. In February, Alain Aspect, Chris Westbrook, and colleagues at the Institut d'Optique in Orsay[1] reported the observation of BEC in a gas of metastable He (He*). Eight days later, a team led by Claude Cohen-Tannoudji and Michèle Leduc at Ecole Normale Supérieure (ENS) in Paris[2] also announced condensation of He*. Although similar in some ways to the alkali and hydrogen condensates, He* condensates pose unique experimental challenges and open up new realms of investigation for both theorists and experimenters.

Role of metastability

In their ground state, ^{4}He atoms can seem rather boring in the laboratory. They have no net spin or charge, and the electronic transitions require wavelengths difficult to access with lasers. They are thus essentially impossible to trap and cool.

In its first excited state, however, ^{4}He is much more manipulable. Denoted spectroscopically by $2\,^3S_1$, the first excited state is metastable: The lifetime of an isolated He* atom is about two hours. The state is a spin triplet, which allows magnetic trapping of He* atoms. And the electronic transitions from the first excited state to higher states fall conveniently in the near infrared, where existing lasers can be used for optical pumping, cooling, and trapping. The ENS He cooling group, initiated by Aspect and Cohen-Tannoudji, has been exploiting these advantages of He* for years, and demonstrated subrecoil cooling in one, two, and three dimensions with He* (see PHYSICS TODAY, January 1996, page 22).

One thing that immediately sets He* apart from the alkali gases is the huge disparity between the internal and external energy scales. The metastable state lies nearly 20 eV above the ground state. That's 11 orders of magnitude larger than the kinetic energy of the atoms at the BEC transition temperature. "Being in an excited metastable state makes the He atoms very fragile," explains Leduc. Because of their huge internal energy, He* atoms tend to ionize anything they collide with, including other He* atoms. This process, called Penning ionization, relaxes the colliding He* atom back to the ground state.

Penning ionization from collisions between two He* atoms is less significant at the low densities used in the earlier laser cooling and trapping studies, but many people thought that this loss mechanism would prevent experiments from reaching the high density of He* atoms necessary for BEC. There was some hope, however, from theoretical predictions first made by Gora Shlyapnikov, Jook Walraven (both now at the FOM Institute for Atomic and Molecular Physics in Amsterdam), and colleagues,[3] and later confirmed by Ian Whittingham (James Cook University) and coworkers.[4] Penning ionization in fully spin-polarized He* is forbidden by spin conservation, and calculations showed that the ionization rate should be five orders of magnitude smaller than the rate in unpolarized He*.

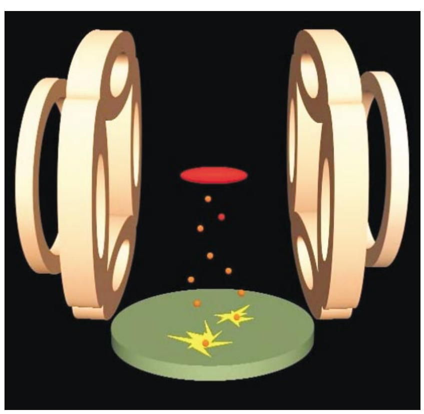

FIGURE 1. EXPERIMENTAL SETUP used at Orsay to observe the first condensate of metastable helium (He*). A microchannel plate (green) detects individual He* atoms (red) when they fall onto it after the magnetic trap produced by the coils (yellow) is turned off.[1] (Courtesy of Olivier Sirjean. Not to scale.)

"The success of the BEC experiments relied on the correctness of this theoretical prediction," says Aspect. "A suppression by a factor of 10^5 is a huge amount, and so when it came, it was a big surprise to many people."

The experiments

The two groups took similar approaches to achieving BEC in He*. A jet of He atoms was excited into the metastable state by an electrical discharge, collimated, and slowed before being confined in a magneto-optical trap. The density was kept relatively low at this stage to prevent excessive Penning ionization. Before switching to a purely magnetic trap, the He* atoms were further cooled with optical molasses and optically pumped into the $m = 1$ sublevel—the only sublevel that's magnetically trapped. Both experiments ended up with a few times 10^8 atoms, fully spin-polarized, in the magnetic trap. Evaporative cooling using radiofrequency-induced spin flips lowered the temperature of the atoms into the microkelvin range. Each group observed the emergence of a sharp peak in the atom density profile as the cloud was cooled through the BEC transition temperature.

The primary difference between the two experiments was in the detection method. Capitalizing on the large internal energy of the metastable atoms, the Orsay group implemented a new detection scheme—a microchannel plate (MCP), illustrated in figure 1. When the magnetic trap was turned off, the He* atoms fell onto the MCP and set off a cascade of electrons. The resulting signal, which had nearly single-atom sensitivity, gave the temporal distribution of He^* atoms hitting the plate, from which the distribution of atoms along one direction could be inferred. To make room for the MCP below their condensate, the Orsay researchers used a cloverleaf design for their trap. The team observed condensation at about 0.7 μK, with up to about 10^5 atoms condensed. With the MCP, the Orsay group was able to study condensates containing as little as a few hundred atoms.

The ENS group used the more traditional technique, common for alkali condensates, of absorption imaging following free expansion with the trap turned off. Figure 2 shows sample images of the He^* condensates. The ENS researchers observed the BEC transition at 4.7 μK, with a maximum of about 5×10^5 atoms in the condensate.

Both groups observe a lifetime of a few seconds for the He^* condensates. It's still too early to tell the extent to which two-body Penning ionization collisions and three-body collisions contribute to the condensate decay rate.

New regimes, opportunities

A key parameter describing condensates is the s-wave scattering length, a, which characterizes the strength of the interactions between atoms. Both groups extracted values on the order of 20 nm for the scattering length in He^*, although the uncertainties are still fairly big. That's about four times larger than rubidium's scattering length, and more than a hundred times greater than hydrogen's. The large value for a made evaporative cooling more efficient—a critical contributor to the experimental success.

The large value of a for He^*, combined with the high density of atoms attainable in these condensates, should allow new regimes of condensate behavior to be probed. The ENS researchers reported that, near their BEC transition, the collision rate between He^* atoms—given by the product of the density, the cross section (proportional to a^2), and the average thermal velocity (high in He^* because of the light mass)—is much larger than the characteristic trap frequencies, placing the condensate in the hydrodynamic regime instead of the so-called collisionless regime studied so far in other condensates.

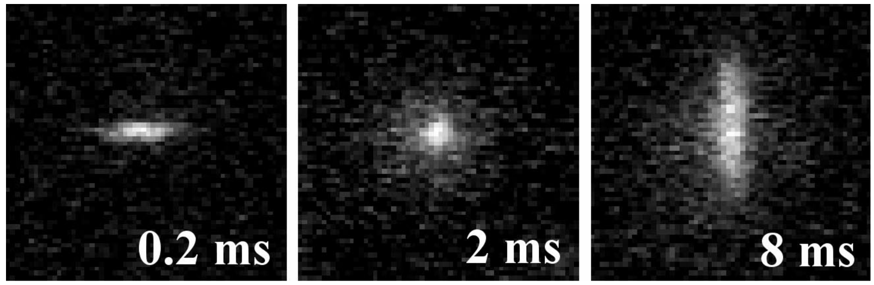

FIGURE 2. ABSORPTION IMAGES of a cloud of metastable helium atoms at Ecole Normale Supérieure, for various times of free expansion. The change in ellipticity is a telltale sign of Bose–Einstein condensation. (Adapted from ref. 2.)

Because of the frequent collisions between He^* atoms, the condensate and the noncondensed atoms (the "thermal cloud") can be in local equilibrium with each other. In this situation, says Allan Griffin (University of Toronto), the system can be described by the two-fluid hydrodynamic equations developed by Lev Landau in 1941 to explain the superfluidity of liquid ^{4}He. For example, the analog of "second sound," in which the condensed and noncondensed components oscillate out of phase, should be observable in the He^* condensate. In 1998, Wolfgang Ketterle's group at MIT reported the onset of hydrodynamic behavior in sodium condensates, but the He^* condensates are the first to be well within this domain.

The large scattering length and high density in He^* condensates have another implication: The scattering length can be a significant fraction of the distance between He^* atoms. The ratio is on the order of several percent in these experiments, compared to less than 0.1% in the alkali condensates. With such a large ratio, He^* condensates should show deviations from the simple mean-field theory that's been used to describe other condensates, notes Charles Clark (NIST Gaithersburg). Forays into this regime have been made by Carl Wieman, Eric Cornell, and colleagues at JILA by tuning the scattering length in ^{85}Rb condensates (see PHYSICS TODAY, August 2000, page 17).

MCP detection opens up new avenues of investigation, too. The Orsay researchers were able to analyze the background ionization recorded with their MCP to obtain real-time information about their condensate's formation and decay. Furthermore, the extremely high sensitivity of the MCP makes possible the study of small condensates far from the thermodynamic limit. The ability to prepare small samples of He^* atoms and detect the atoms one at a time also creates new possibilities in quantum atom optics experiments, such as measurements of atom interference, coherence, and density correlations on an atom-by-atom basis.

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References

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Dramatic Evidence Seen for Collective Behavior among Electrons in Closely Separated Layers

The Josephson effect is a dramatic macroscopic manifestation of quantum mechanics: If you separate two superconductors by a thin insulating barrier, a current can flow across the junction with no voltage applied. Similar behavior was recently seen in a system that involves neither superconductors nor superfluids. Experimenters from Caltech and Bell Labs, Lucent Technologies, formed two parallel layers of electrons, separated them by a very small distance, and measured the tunneling conductance between them, that is, the differential change in interlayer current with voltage.[1] As the voltage dropped to zero, the researchers saw an enormous peak in the conductance—much more than could be explained by ordinary tunneling. Such strongly enhanced conductance, shown in figure 1a, suggests that electrons in

> Theorists describe the two-layer system as a Josephson junction, an exciton condensate, or a ferromagnet.