Cold atoms stay cool

Methods for studying Bose–Einstein condensation in ultracold gases have been under development for over 40 years. A highly sophisticated suite of techniques has emerged from rapid technological advances that show no sign of slowing down.

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The sophistication of present experiments with ultracold gases would be inconceivable without the great instrumental advances following the discovery of Bose–Einstein condensation (BEC) in 1995[1,2]. The first experiments were fascinating because of the BEC phenomenon itself. It took no more than a cloud of 1,000 trapped rubidium atoms and a good digital camera to observe the condensate as a distinct feature at the centre. Today, with the first condensate in space[3], it is good to recall the advances that brought us here.

Let us consider the cascade of experimental methods that have been applied to push the boundaries of what can be achieved with ultracold gases. At the time of the discovery, the search for BEC had been a small but recognized field for many years. In 1980, it had been shown that a gas of spin-polarized bosonic hydrogen[4] and fermionic deuterium[5] atoms could be trapped and studied for minutes at subkelvin temperatures. This regime was reached under quasi-equilibrium conditions using thermal contact with the surface of superfluid helium.

In the earliest experiments, the total number of atoms was determined by removing their trap after a variable holding time and measuring the heat of recombination into molecules using a cryogenic bolometer[5]. The approach of using the free evolution to probe ultracold gases has proven invaluable to the present day, for example, to study shape oscillations or coherence properties in time-of-flight measurements. In the case of hydrogen, rapid progress was also made with non-destructive methods, such as measuring pressure at constant volume or by using magnetic resonance methods to follow the evolution of internal states[6].

By the mid-1980s there was a fairly complete understanding of the relaxation and recombination phenomena limiting the stability of the gas. In particular, recombination losses that were enhanced by the superfluid helium surface severely limited the prospects for reaching the BEC regime. This not only made the search for surface-free confinement methods the logical next step but also closed the existing detection toolbox of the experimentalist.

Progress was made by loading cryogenically cooled gases into a magnetic potential well designed to keep the atoms away from surrounding surfaces[7,8]. The loading principle is based on thermal equilibration of the atoms by collisions in the trapping potential. The energy introduced by trapping is carried away by 'hot' atoms from the high-energy tail of the thermal distribution escaping the trap and colliding with surrounding surfaces. Even better, by completely removing the hot atoms, the cooling can be continued to temperatures far below the surface temperature[9]. During this evaporative cooling process the gas volume contracts in the trap, enabling the gas density — a key parameter for achieving BEC — to be conserved during the process.

Alongside these developments in studying hydrogen, the neutron became the first neutral particle trapped in a magnetic storage ring[10] and optical laser cooling had been demonstrated with trapped ions[11,12]. In the wake of these developments, the first neutral atom to be trapped was sodium. Using a 'Zeeman slower', a beam of sodium atoms was optically cooled to form an ultracold atomic cloud that could be held at rest in a magnetic trap[13].

The discovery of optical molasses[14], sub-Doppler cooling in optical lattices[15] and the development of time-of-flight absorption imaging by digital cameras[15] strongly stimulated the field. With the realization of the magneto-optical trap, it became possible to both cool and trap the atoms in one and the same configuration[16]. These great achievements on optical cooling and trapping were recognized with the Nobel Prize in Physics in 1997.

The optical methods used with the alkalis have the advantage of being much more experimentally flexible compared with exotic methods used with hydrogen. The availability of single-mode diode lasers, the realization of the vapour cell magneto-optical trap[17] and later the time-orbiting potential trap[18] simplified entry into the field and attracted the interest of a growing audience.

Scientifically, these advances broadened the search for BEC from hydrogen, as an exceptional atom with unique properties, to any bosonic element from the periodic table that would be accessible to an appropriate optical cooling scheme. Both the optical and the evaporative approaches to cooling and trapping turned out to be essential for meeting the conditions for BEC. They also enabled the surge of experiments with Bose–Einstein condensed gases following the Nobel-Prize-winning discoveries using rubidium[1] and sodium[2] atoms in 1995.

After the first BEC experiments, the field broadened and began to overlap with condensed-matter physics. Advances in optical lattices enabled the study of quantum phases and phase transitions such as the superfluid-to-Mott-insulator transition[19]. The present status of this direction of quantum engineering using methods from Floquet theory is discussed in ref. [20] in this *Nature Physics* Insight. Microscopic imaging for individual atom and spin measurements, discussed in ref. [21], have also brought ultracold gas measurements closer to the methods familiar in condensed-matter studies. A review of the currently available spectroscopic probes is given in ref. [22].

The search for new condensates was successful. The achievement of BEC using electronically excited metastable helium atoms was a particular milestone as it provided single-atom detection sensitivity in three dimensions and a new tool for experimental quantum optics[23].

More generally, inter-atomic interactions can be controlled by using magnetic fields to manipulate Feshbach resonances that occur during atomic collisions[24]. Together with advances in optical dipole traps, these have helped achieve BEC in a broad class of bosonic systems, with the latest developments discussed in ref. [25].

Manipulation of Feshbach resonances enabled the thermalization in Fermi gases[26], soon followed by the formation of molecular condensates[27,28]. By tuning interactions in a Bose gas, one can cover the range from the weakly interacting limit to strongly interacting conditions like those in liquid helium[29]. By passing through the Feshbach resonance a special, universal ‘unitarity’ regime can be reached where the two-body elastic cross-section reaches the maximum value allowed by quantum mechanics.

Experiments like these have established fluidic ultracold atomic systems without a lattice as a platform suited for accurate quantum simulation[30–32]. Developments in this direction using the rich properties of lanthanide atoms, reviewed in ref. [33], have enabled the observation of the consequences of long-range interactions such as magnetic droplet formation[34] and supersolidity[35].

The advances in using optical tweezers to control atoms and molecules, reviewed in ref. [36], seemed far beyond the horizon for a long time, especially because optical cooling of molecules was inconceivable. The impact of the latest experiments reminds me of the excitement after the first observation of quantum jumps with a single ion[37] and of the first dipole trap[38].

The development of optical box potentials as discussed in ref. [39] provides new trapping geometries that are essential for studying gases under homogeneous conditions. This is research in the best tradition of ultracold atom physics and responds to issues that have been on the wish list of theoreticians for a long time.

The seven contributions to this Insight show that the technological innovation in the field of ultracold atoms is as alive as ever. As I wrote in 1995[40]: a fascinating period lies ahead. ❐

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Competing interests

The author declares no competing interests.