Happy birthday BEC

Wolfgang Ketterle

Bose–Einstein condensation in atomic gases was first observed in 1995. As we look back at the past 20 years of this thriving field, it's clear that there is much to celebrate.

Bose–Einstein condensation (BEC) has changed the face of atomic physics. BEC is for atoms or matter waves what the laser is for photons: a macroscopically occupied quantum state. It was regarded as an elusive goal until it was discovered in 1995. Although BEC was immediately viewed as a major accomplishment, its impact has far exceeded expectations. Twenty years on, there is no question that the field remains exciting. And maybe the best is yet to come.

With the advent of BEC, it became possible to obtain nanokelvin temperatures and create samples of atoms almost free of entropy. Within a very short time, most of the many groups working on laser cooling transitioned to studies of Bose–Einstein condensates. Evaporative cooling of atoms was just so much more robust and applicable to higher densities than any sub-recoil laser-cooling scheme. First demonstrated in 1988 by Thomas Greytak, Harald Hess and Dan Kleppner, evaporative cooling was the enabling technology for the first atomic BECs, and is still the only cooling method that works for cooling atoms to quantum degeneracy.

BEC was also immediately recognized as a new quantum liquid, extending the tradition from the superfluid quantum liquids helium-3 and helium-4 to gaseous systems at a billion times lower density. And when it became a reality, there was an immediate shopping list of scientific goals with quantum control and precision measurements coming from laser cooling and atomic physics, and the study of phase transitions, sound and other collective excitations, vortices and superfluidity drawing from quantum liquids. Most of these goals were accomplished in the years that followed, with the exception of precision measurements, hampered by the high atomic densities in BECs that introduce interaction shifts of spectral signals as a major systematic uncertainty. Instead, lower-density laser-cooled samples are often used. But what most people could not imagine in 1995 was how many other scientific directions could take advantage of BECs. I have often said that even in my boldest dreams, I would not have imagined how remarkably the field would develop. To a large degree, this reflects the variety of systems and methods that atomic physics brought to BEC research.

First, many atomic species have now been condensed. This includes atoms that cannot be confined in magnetic traps, one of the key technologies used in earlier BEC work. They can, however, be confined in optical traps — a technique that has undergone substantial developments. Second, evaporative cooling to quantum degeneracy has been extended to fermionic atoms and to molecules (more about this below).

Third, mixtures of different atomic species are being studied, including spinor condensates, which are mixtures of atoms in different internal states that interconvert depending on external parameters, resulting in a rich phase diagram. Fourth, Feshbach resonances (scattering resonances allowing a wide tunability of interactions via magnetic fields) and optical lattices became powerful new methods. Fifth, laser and optical technology has rapidly advanced. Laser sources are now much cheaper and more reliable, and it is possible to do experiments with many different lasers of different colours. This is a big step forward from my own labs in the mid and late 1990s, which fully depended on the dye lasers that are now almost universally thought of as giant extinct species.

Some important extensions of BEC were surprisingly straightforward because they continued to use alkali atoms, for which almost all cooling and trapping methods were first developed. Fermionic isotopes of potassium and lithium, for example, could be cooled to degeneracy using the same basic methods as those used for bosonic gases — avoiding the freeze-out of elastic collisions by using a two-component gas. The crossover from BEC to BCS superfluidity was accessible by means of further cooling, which induced the fermions to form pairs and eventually become superfluid. Ultimately, these experiments were not much more complicated than the early BEC experiments. The difference was that researchers had to understand Feshbach resonances and cold collision physics in order to choose the right conditions (in particular the magnetic field controlling the atomic interactions).

Ultracold molecules were assembled from ultracold alkali atoms using Feshbach resonances. Currently, this approach features the lowest temperatures and highest phase-space densities achieved so far with molecules. A new subfield, ultracold chemistry, is opening up. I continue to be surprised at how large a market share of research the alkali atoms still command.

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This photo, taken at the 2015 BEC conference in Spain, shows past, current and future chairmen of this conference (1993–2017), together with three Nobel laureates and Dan Kleppner, an early pioneer in BEC research. Front row: Christophe Salomon, Ehud Altman, Eric Cornell, Thierry Giamarchi. Back row: Ignacio Cirac, Tilman Esslinger, Jook Walraven, Massimo Inguscio, Wolfgang Ketterle, Sandro Stringari, Dan Kleppner, Gora Shlyapnikov, Yvan Castin, Peter Zoller, Maciej Lewenstein and Bill Phillips.

The systems and methods mentioned above are now often combined in a platform called a quantum simulator. This is a toolbox in which atoms, multiple laser beams, and radio-frequency or microwave radiation are used to 'quantum engineer' interesting, often paradigmatic, Hamiltonians to study their properties. Prime examples are the BEC–BCS crossover, fermions with infinitely strong interactions, population-imbalanced fermion systems, Bose–Hubbard and Fermi–Hubbard models, and Anderson localization.

Many of the new developments featured at the international conference on Bose–Einstein condensation held in September this year. These conferences started in 1993 when progress towards achieving BEC intensified. Despite keeping the name, the meeting now covers all frontiers in quantum gases. The 2015 conference opened with a celebratory session 'BEC 20 years', but most speakers, after some historical remarks, focused on new results. Bill Phillips, 1997 Nobel Laureate for laser cooling, captured the spirit of the meeting in a talk entitled '40 years of laser cooling, 20 years of BEC: still surprises'.

It seemed apt that the 2015 senior BEC prize was given to Greytak, Hess and Kleppner for their early demonstration of evaporative cooling of atoms. The award talk highlighted the obstacles during the early days of research towards Bose–Einstein condensates, and the solutions that many younger researchers now take for granted.

Some of the new frontiers discussed at the meeting include systems such as ultracold atomic gases with Rydberg excitations to obtain strong interactions and correlations, highly magnetic atoms that show strong dipolar interactions, and quantum fluids of photons. New techniques are being developed, such as single-atom microscopy, and shaping quantum gases into two reservoirs connected by a thin channel for transport measurements. And new scientific avenues have emerged, including spin–orbit coupling and artificial gauge fields, the creation of topological defects (Kibble–Zurek physics) during quenches across the BEC phase transition, disorder and many-body localization, ergodicity and pre-thermalization, the entanglement of few atoms, and polarons in BECs and Fermi gases. Although the community of researchers in this field has grown rapidly, it still feels like a big family marked by a friendly atmosphere with a collaborative spirit.

One key goal for the future is to obtain a deeper understanding of entanglement, strong interactions and correlations in few- and many-body systems. This can be realized by using ultracold atoms and molecules to assemble interesting quantum systems. Materials with topological properties, including the fractional quantum Hall effect, topological insulators and Majorana fermions, new forms of superfluidity (such as *p*-wave and *d*-wave pairing, FFLO states, or models for high-temperature superconductors) and frustrated spin systems all rank high on this list. A challenge is to use fermions as particles and bosons as fields to simulate dynamic gauge fields, and to study toy models for quantum chromodynamics.

Atomic physics can go beyond the realizations available to an electron system by using bosonic and fermionic atoms in various spin states — finding the bosonic version of fractional quantum Hall states, for example, or superfluidity in a three-component Fermi system. But almost certainly, there will be surprises and unexpected breakthroughs. In the long term, the hope is that insight into new quantum phases of matter will pave the way towards fundamentally new materials and new devices. ❐

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