BOSE-EINSTEIN CONDENSATION – S.N. BOSE'S LEGACY LIVES ON

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Satyendra Nath Bose and Albert Einstein predicted Bose-Einstein condensation in 1924 which is a new form of matter – a superfluid gas. This was realized in atomic gases in 1995. As we look back at this thriving field, it's clear that there is much to celebrate, and much more excitement to come.

Bose-Einstein condensation (BEC) has changed the face of atomic physics. It 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 exceed expectations. Now, more than 20 years later, 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 BECs. 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 method of choice 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 immediately a shopping list of scientific directions quantum control and precision measurement 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 couldn't 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 dramatically 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 major 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

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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 colors. 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.

Another platform for Bose-Einstein condensation are excitons and polaritons – bosonic excitations in solid materials. Since these bosons are much lighter than atoms, the BEC transition temperature is much higher, even room temperature is possible.

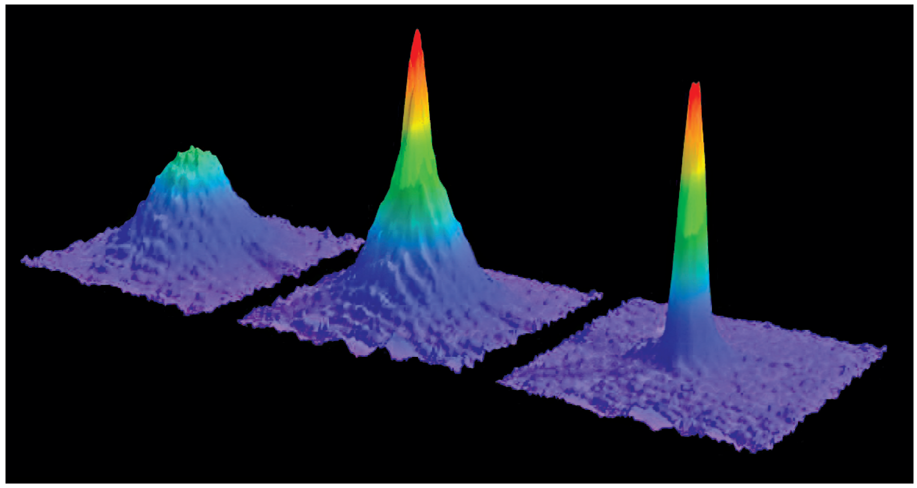

Fig. 1. One of the first observations of Bose-Einstein condensation (MIT, 1995). Shown are absorption (or shadow) pictures of the atomic cloud after ballistic expansion. The Bose-Einstein condensate is characterized by its slow expansion observed after 6 msec time of flight. The left picture shows an expanding cloud cooled to just above the transition point; middle: just after the condensate appeared; right: after further evaporative cooling has left an almost pure condensate. The width of the images is 1.0 mm. The total number of atoms at the phase transition is about $7x10^5$, the temperature at the transition point is 2 microkelvin.

Some major extensions of BEC were surprisingly straight forward 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. Further cooling induced the fermions to form pairs and to become superfluid. Using a Feshbach resonance to adjust the atomic interactions, the nature of the pairing was changed from tight molecular pairing to a looser form of pairing analogous to Cooper pairs of electrons in superconductors and the BEC-BCS crossover was mapped out (BCS stands for the Bardeen-Cooper-Schrieffer theory for the simplest form of superconductors). Ultimately, these experiments weren't 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 approaches to ultracold molecules features lowest temperatures and highest phase space densities. A new subfield, ultracold chemistry, is opening up. Tri-atomic molecules (so called Effimov trimers) provided new insight into universal features of three-body systems. I continue to be surprised at how big a market share of research the alkali atoms still command.

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.

All of the recent developments are featured at the Biannual International Conferences on Bose–Einstein condensation. 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 historic 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 major obstacles during the early days of research towards Bose–Einstein condensates, and the solutions that many younger researchers now take for granted.

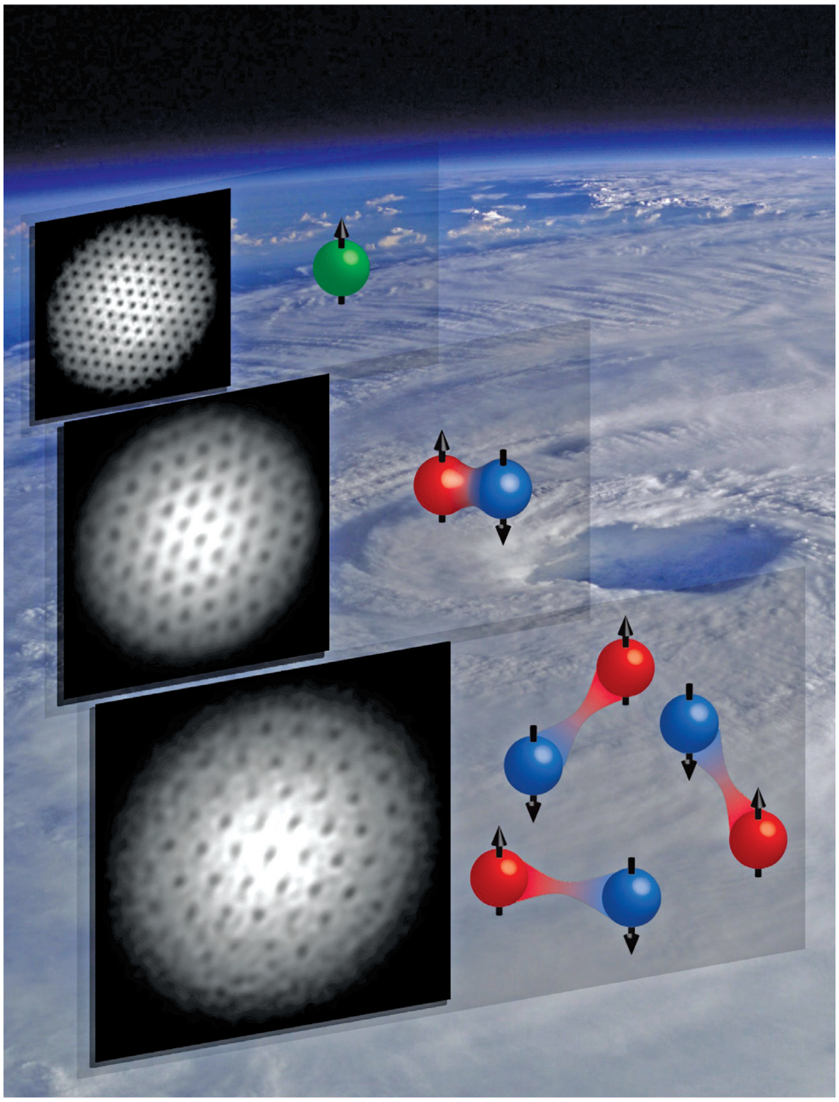

Fig. 2. Vortices in quantum gases: Shown is a Vortex pattern in bosonic Sodium atoms (green cartoon) in a magnetic trap, Vortices in tightly bound Lithium molecules (red-blue cartoon) and a vortex lattice in loosely bound Fermion pairs created on the "BCS-side" of a Feshbach resonance. The background shows a classical vortex (Hurricane Isabel in summer 2003, NASA image ISS007E14887).

Some of the new frontiers include new 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 major 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 (including p-wave and d-wave pairing, FFLO states, 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, such as toy models for quantum electrodynamics and 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.

S.N. Bose was born on January 1, 1894, 125 years ago. I am sure he would have been very pleased to see in how many ways his theoretical concepts are now applied. ❐

References

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2. This article is based on an earlier Nature Physics paper by the same author (Nature Physics 11, 982 (2015))