The 2001 Nobel Prize in Physics

Bose–Einstein Condensation

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This year's Nobel Prize in Physics has been jointly awarded to Eric A Cornell of the National Institute of Standards and Technology, Boulder (USA), Wolfgang Ketterle of the Massachusetts Institute of Technology, Cambridge (USA), and Carl E Wieman of the University of Colorado, Boulder (USA). They have been cited "for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates". The scientists have been recognized for their pioneering work in a field that has grown explosively around the world in the past few years. Though the phenomenon of Bose–Einstein condensation (BEC) was predicted by Einstein in 1925 (based on the new statistics of Bose), it was observed only in 1995. In this article, we review the basic physics behind the phenomenon, the experimental techniques involved in achieving it, and highlight some of the potential applications of condensates.

The story of BEC begins in 1924 when the young Indian physicist S N Bose gave a new derivation of the Planck radiation law. He was able to derive the law by reducing the problem to one of counting or statistics: how to assign particles (photons) to cells of energy $h\nu$ while keeping the total energy constant. Einstein realized the importance of the derivation for developing a quantum theory of statistical mechanics. He argued that if the photon gas obeyed the statistics of Bose, so should material particles in an ideal gas. Carrying this analogy further, he showed that the quantum gas would undergo a phase transition at a sufficiently low temperature when a large fraction of the atoms would condense into the lowest energy state. This is a

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phase transition in the sense of a sudden change in the state of the system, just like steam (gaseous state) changes abruptly to water (liquid state) when cooled below 100°C. But it is a strange state because it does not depend on the interactions of the particles in the system, only on the fact that they obey a kind of quantum statistics.

In modern physics, the phenomenon is understood to arise from the fact that particles obeying Bose–Einstein statistics (called bosons) 'prefer' to be in the same state. This is unlike particles that obey Fermi–Dirac statistics (fermions), and therefore the Pauli exclusion principle, which states that no two of them can be in the same state. In some sense bosons try to 'imitate' each other and aggregate in a group where they can lose their identity and be all alike! With this property of bosons in mind, imagine a gas of bosons at some finite temperature. The particles distribute the total energy amongst themselves and occupy different energy states. As the temperature is lowered, the desire of the particles to be in the same state starts to dominate, until a point is reached when a large fraction of the particles occupies the lowest energy state. If any particle from this state gains some energy and leaves the group, his friends quickly pull him back to maintain their number! This is a Bose–Einstein condensate, with the condensed particles behaving like a single quantum entity.

Each H atom behaves like a little magnet and, if it were aligned anti-parallel to the external field, it would be trapped near the point where the field is a minimum.

The point at which 'the desire for the particles to be in the same state starts to dominate' can be made more precise by considering the quantum or wave nature of the particles in greater detail. From the de Broglie relation, each particle has a wavelength λ_{dB} given by h/mv, where m is the mass and v is the velocity. As the temperature is lowered, the mean velocity of the particles decreases and the de Broglie wavelength increases. BEC occurs when λ_{dB} becomes comparable to the average interparticle separation. At this point, the wave functions of the particles overlap and they become aware of their likeness for each other! The average interparticle separation for a gas with number density n is $n^{-1/3}$, and from kinetic theory, the mean de Broglie wavelength of gas particles at a temperature T is $h/(2\pi mkT)^{1/2}$. For the wave functions to overlap, the product $n\lambda_{dB}^3$ should be of the order 1. A more rigorous analysis shows that BEC occurs when the dimensionless phase-space density $n\lambda_{dB}^3$ exceeds 2.612.

Figure 1. Carl E Wieman (left) and Eric A Cornell.

In the early days, it was believed that BEC was only a theoretical prediction and was not applicable to real gases. However, the observation of superfluidity in liquid He in 1938 made people realize that this was a manifestation of BEC, even though it occurred not in an ideal gas but in a liquid with fairly strong interactions. BEC in a non-interacting gas was now considered a real possibility. The first serious experimental quest started in the early 1980s using spin-polarized atomic hydrogen. There were two features of H that were attractive: it was a model system in which calculations could be made from first principles, and it remained a gas down to absolute zero temperature without forming a liquid or solid. Spin-polarized H could also be trapped using suitable magnetic fields. Each H atom behaves like a little magnet and, if it were aligned anti-parallel to the external field, it would be trapped near the point where the field is a minimum. Using cryogenic techniques, the gas was cooled to about 1 K and then loaded into a magnetic trap.

Figure 2. Wolfgang Ketterle

One of the major developments to come out of these efforts was the proposal in 1986 by Harald Hess, then a post-doctoral worker with Dan Kleppner at MIT, to use evaporative cooling to lower the temperature and reach BEC. The idea in evaporative cooling is to selectively remove the hottest atoms from the trap, and then allow the remaining atoms to thermalize. Since the remaining atoms have lower energy, they thermalize to a lower temperature. This is similar to cooling coffee in a cup: the hottest particles near the top evaporate and take away the heat, while the remaining particles get colder. The MIT group of Kleppner and Greytak demonstrated evaporative cooling of spin-polarized H by lowering the height of the magnetic trap. By 1992, they had come within a tantalizing factor of 3 of observing BEC but were stopped short due to technical problems.

The use of evaporative cooling was a major development in the 1980s.

Meanwhile, a parallel effort in observing BEC using alkali atoms was getting underway. The main impetus for this was to see if the tremendous developments that occurred in the late 1980s in using lasers to cool atomic clouds could be used to achieve BEC. Alkali atoms could be maintained in a gaseous state if the density was low, typically less than 10^{14} atoms/cm^3. But this meant that BEC would occur only at temperatures below 1 μK. Laser-cooling techniques had indeed achieved temperatures in the range of a few μK, with a corresponding increase in phase-space density of about 15 orders of magnitude. However, there were limitations in the achievable temperature due to heating from the presence of scattered photons in the cloud. One advance to this problem came from the MIT group of Dave Pritchard. His then post-doctoral worker, Wolfgang Ketterle, proposed using a special magneto-optic trap in which the coldest atoms get shelved in a dark state where they do not interact with the laser anymore. Since these atoms do not see the light, they do not get heated out of the trap. This helped improve the density by another order of magnitude, but BEC was still a factor of million away.

Pritchard's group at MIT also demonstrated magnetic trapping of sodium at around the same time. Pritchard and his student, Kris Helmerson, proposed a new technique for evaporative cooling in such a trap: *rf*-induced evaporation. Instead of lowering the magnetic field to cause the hottest atoms to escape, as was done in the spin-polarized hydrogen experiments, they proposed using an *rf* field tuned to flip the spin of the hottest atoms. The magnetic trap is a potential well for atoms whose spin is anti-parallel to the magnetic field, but is a potential hill for atoms whose spin is parallel. Therefore, once the spin of the atom is flipped, it would find itself on the side of a potential hill and slide out. The beauty of this technique is that the *rf* frequency determines which atoms get flipped, while the trapping fields remain unchanged. Pritchard's group was however unable to demonstrate evaporative cooling in their magnetic trap because the density was too low.

Laser cooling and evaporative cooling each had their limitations because they required different regimes. Laser cooling works best at low densities while evaporative cooling works at high densities when collisions enable rapid rethermalization. Therefore, in the early 1990s, a few groups started using a hybrid approach to achieve BEC, i.e. first cool atoms to the microkelvin range using laser cooling, and then load them into a magnetic trap for evaporative cooling. By 1994, two groups were leading the race to obtain BEC: the Colorado group of Cornell and Wieman, and the MIT group of Ketterle. Both groups had demonstrated *rf*-induced evaporative cooling in a magnetic trap, but found that there was a new limitation, namely a hole in the bottom of the trap from which atoms leaked out. The hole was actually the field zero at the centre of the trap. When atoms crossed this point, there was no field to keep the atom's spin aligned, so it could flip its spin and go into the untrapped state. As the cloud got colder, atoms spent more time near the hole and were quickly lost from the trap.

Ketterle's solution to plug the hole was to use a tightly focussed Ar-ion laser beam at the trap centre. The optical force from the laser beam kept the atoms out of this region, and, since the laser frequency was very far from the resonance frequency of the atoms, it did not cause any absorption or heating. The technique proved to be an immediate success and gave Ketterle's team an increase of about 3 orders of magnitude in phase-space density. But again technical problems limited the final observation of BEC.

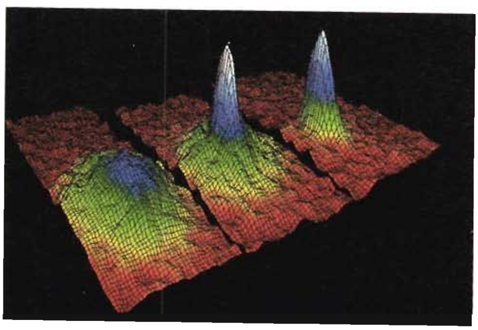

Figure 3. Bose–Einstein condensation of ^{87}Rb at Colorado. False-colour images display the velocity distribution of the cloud of Rb atoms at (a) just before the appearance of the Bose–Einstein condensate, (b) just after the appearance of the condensate and (c) after further evaporation left a sample of nearly pure condensate. The field of view of each frame is 200 × 270 micrometres, and corresponds to the distance the atoms have moved in about 1/20 of a second. The colour corresponds to the number of atoms at each velocity, with red being the fewest and white being the most.

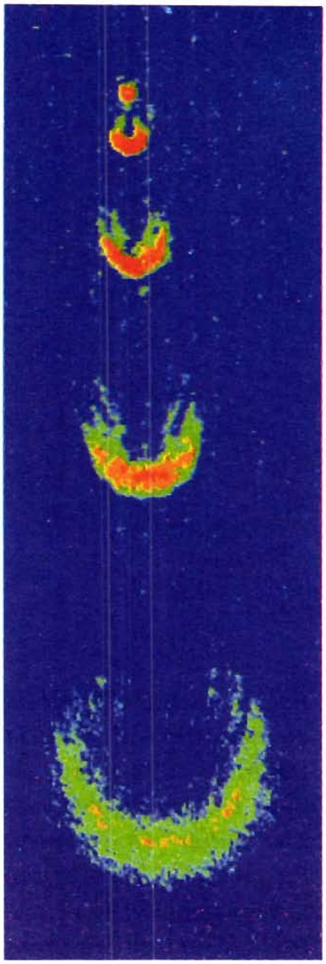

Figure 4. The MIT atom laser. A Bose condensate of sodium atoms (small spot at the top) was trapped between two magnetic field coils by having the magnetic moments of the atoms anti-parallel to the magnetic field. Short pulses of an oscillating magnetic field flipped the magnetic moment of an adjustable fraction of the atoms. These atoms were no longer confined and propagated as a coherent matter wave accelerated by gravity. Every five msec, a new pulse was created. The image (field of view: 2.5 mm × 5 mm) shows several propagating pulses. The curved shape of the pulses was caused by gravity and forces between the atoms.

Cornell had a different solution to the leaky trap problem: the time-orbiting potential (TOP) trap. His idea can be understood in the following way. The magnetic trap has a field whose magnitude increases linearly from zero as you move away from the trap centre in any direction. The hole in the trap is the field zero point. Now, if you add a constant external field to this configuration, the hole does not disappear, it just moves to a new location depending on the strength and direction of the external field. Atoms will eventually find this new hole and leak out of it. However, Cornell's idea was that if you move the location of the hole faster than the average time taken for atoms to find it, the atoms will be constantly chasing the hole and never find it! A smooth way to achieve this is to add a rotating field that moves the hole in a circle. The time-averaged potential is then a smooth potential well with a non-zero minimum.

Plugging the leaky trap proved to be the final hurdle in achieving BEC. In July 1995, Cornell and Wieman announced that they had observed BEC in a gas of ^{87}Rb atoms. The transition temperature was a chilling 170 nK, making it the coldest point in the universe! The researchers had imaged the cloud by first allowing it to expand and then illuminating it with a pulse of resonant light. The light absorbed by the cloud cast a shadow on a CCD camera. The 'darkness' of the shadow gave an estimate of the number of atoms in any region. The striking feature of the work was that there were three clear and distinct signatures of BEC, so clear that any skeptic would be immediately convinced. (i) The appearance of the condensate was marked by a narrow, intense peak of atoms near the centre, corresponding to the ground state of the trap. (ii) As the temperature was lowered below the transition temperature, the density of atoms in the peak increased abruptly, indicating a phase transition. (iii) The atoms in the peak had a nonthermal velocity distribution as predicted by quantum mechanics for the ground state of the trap, thus indicating that all these atoms were in the same quantum state.

BEC is to matter waves what a laser is to light waves.

Soon after this, Ketterle's group observed BEC in a cloud of ^{23}Na atoms. As against the few thousand condensate atoms in the Colorado experiment, they had more than a million atoms in the condensate. This enabled them to do many quantitative experiments on the fundamental properties of the condensate. For example, they were able to show that when two condensates were combined, they formed an interference pattern, indicating that the atoms were all phase coherent. They were also able to extract a few atoms from the condensate at a time to form a primitive version of a pulsed atom laser: a beam of atoms that are in the same quantum state. They could excite collective modes in the condensate and watch the atoms slosh back and forth. These results matched the theoretical predictions very well.

BEC in atomic gases has since been achieved in several laboratories around the world. Apart from Rb and Na, it has been observed in the alkali atom Li. The atomic H group at MIT achieved it in 1998. Metastable He has also been cooled to the BEC limit. Recently, a Rb BEC was obtained by evaporative cooling in an all-optical trap. The trap is formed using tightly focussed laser beams, thus eliminating the need for strong magnetic fields. The variety of systems and techniques to get BEC promises many applications for condensates. The primary application, of course, is as a fertile testing ground for our understanding of many-body physics, bringing together the fields of atomic physics and condensed-matter physics. In precision measurements, the availability of a giant coherent atom should give enormous increase in sensitivity. BECs could also impact the emerging field of nanotechnology since the ability to manipulate atoms greatly increases with their coherence. In some ways, BEC is to matter waves what a laser is to light waves. Just as lasers have impacted our daily lives in ways that were impossible to imagine when they were first invented, BECs promise to impact the technology of the future in exciting new ways.

In conclusion, let me acknowledge that the experiments using BECs have been truly beautiful illustrations of quantum physics. Many of the results have appeared on the covers of scientific journals and magazines. Some have even appeared in the popular press. Perhaps it is the name Einstein in the word BEC, which holds the magic that catches everyone's attention. But the fact remains that even scientists, who are better known for their austere reliance on cold facts, have described the experiments using BECs as being 'beautiful', a word that is often reserved for the finer arts. I am personally very pleased that these physics experiments can trigger other people to see beauty, and I mentioned this to Wolfgang Ketterle when I sent him a congratulatory email on winning the Nobel Prize. So let me end this article with a quote from his response: "beauty is created by nature, sometimes we are able to make it visible". In these dark and ugly times, when we are surrounded by terrorism and war, I hope that more scientists are able to make the beauty in nature visible to others, and help us rise above the narrow-mindedness that leads to war.

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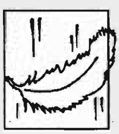
Suggested Reading

[1] http://jilawww.colorado.edu/bec/
[2] http://www.colorado.edu/physics/2000/bec/index.html
[3] http://cua.mit.edu/ketterle_group/



The whole of science is nothing more than a refinement of everyday thinking.

Albert Einstein