The 2001 Nobel Prize in Physics: Bose–Einstein condensation

The 2001 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 phenomenon of Bose–Einstein condensation (BEC) was originally predicted by Einstein in 1925 by applying the then new statistics of Bose to an ideal gas. Even though signatures of this novel phase of matter were seen in phenomena such as superfluidity and superconductivity, it was only in 1995 that BEC was first achieved in a dilute, non-interacting gas of alkali atoms. This year’s Nobel Laureates pioneered the efforts to achieve BEC in such alkali-atom gases, and the field has grown explosively around the world since then. In this article, I 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 *hn*, 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 phase transition in the sense of a sudden change in the state of the system, just like water changes abruptly from the vapour state to the 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 fact, the strange nature of this prediction prompted Einstein to write the following to Ehrenfest in 1924, ‘From a certain temperature on, the molecules “condense” without attractive forces, that is, they accumulate at zero velocity. The theory is pretty, but is there also some truth to it?’

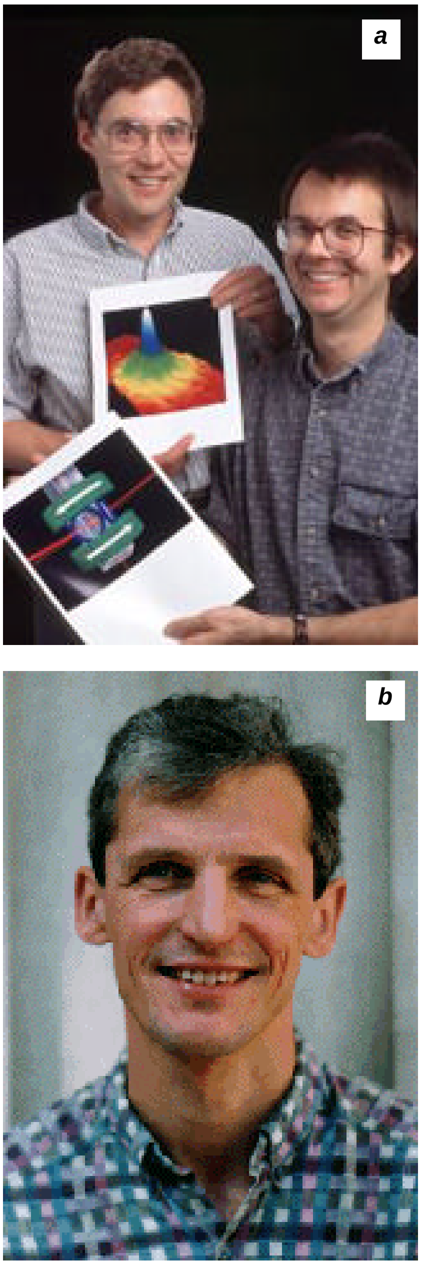

Figure 1. ***a***, Carl E. Wieman (left) and Eric A. Cornell; ***b***, Wolfgang Ketterle.

In modern physics, the phenomenon is understood to arise from the fact that, for particles obeying Bose–Einstein statistics (called bosons), the probability of scattering into a state increases with the number of particles already in that state. This is unlike particles that obey Fermi–Dirac statistics (fermions), and therefore the Pauli exclusion principle, which implies that no two particles can be in the same state. Thus bosons try to 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 probability 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, the remaining particles quickly cause it to rescatter back into the group! This is a Bose–Einstein condensate, with the condensed particles behaving like a single quantum entity.

The point at which ‘the probability 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 l_{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 l_{dB} becomes comparable to the average interparticle separation. At this point, the wave functions of the particles overlap and they start ‘interacting’, though only in a statistical sense. 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 $h/(2pmkT)^{1/2}$. For the wave functions to overlap, this product should be of order 1. A more rigorous analysis shows that BEC occurs when the dimensionless phase-space density $n\,l_{dB}^{3}$ exceeds 2.612.

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. A typical trap geometry to create such a field minimum is to use two current-carrying coils in the anti-Helmholtz configuration, which produces a spherical quadrupole field. To load the magnetic trap, the H gas is first cooled below 1 K using cryogenic techniques.

One of the major developments to come out of these efforts was the proposal in 1986 by Harald Hess 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 total energy, they thermalize to a lower temperature. In order for this to work, the time taken for thermalization due to collisions must be much shorter than the trap lifetime, so that the particles remain in the trap long enough to attain the lower temperature. The MIT group of Kleppner and Greytak demonstrated evaporative cooling of spin-polarized H by lowering the height of the magnetic trap successively. By 1992, they had come within a tantalizing factor of 3 of observing BEC but were stopped short due to technical problems.

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 that 10^{15} 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-doc (and one of this year's laureates), 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 to the field. 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

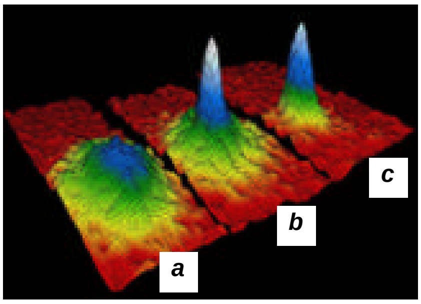

Figure 2. BEC of ^{87}Rb at Colorado. False-colour images display the velocity distribution of the cloud of Rb atoms at (***a***) just before the appearance of the Bose–Einstein condensate, (***b***) just after the appearance of the condensate and (***c***) after further evaporation left a sample of nearly pure condensate. The field of view of each frame is 200 mm × 270 μm, 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. (Courtesy: Eric Cornell)

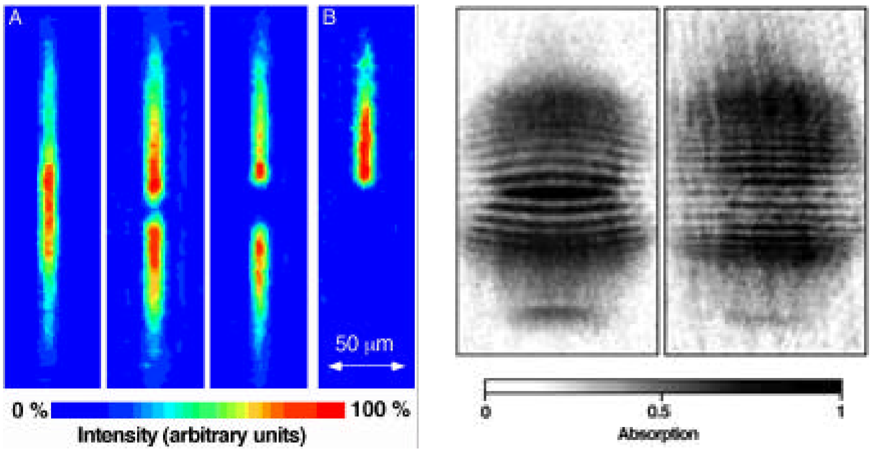

Figure 3. Interference of two Bose condensates (MIT). The two condensates were created by first cutting the magnetic trap in half with an argon-ion laser beam. The sodium atoms in the two halves of the trap were cooled to form two independent Bose condensates, as shown in the figure on the left. At this point, the laser and the magnetic fields were quickly turned off, allowing the atoms to fall and expand freely. As the two condensates began to overlap with one another, they formed interference fringes as seen in the images on the right. This shows that the condensate behaves like a giant matter wave. (Courtesy: Wolfgang Ketterle)

the trapping fields remain unchanged. Pritchard's group was, however, unable to demonstrate evaporative cooling in their magnetic trap, because the density of atoms was too low to facilitate rapid rethermalization.

Laser cooling and evaporative cooling each had its limitations, because they required different regimes to work effectively. Laser cooling works best at low atomic densities where each atom interacts with the light almost independently. However, evaporative cooling is effective 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 the atoms to the microkelvin range using laser cooling, and then load them into a magnetic trap where they can be further cooled using evaporative cooling. By the year 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 in the anti-parallel state, 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-focused 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 he had a technical problem in terms of directional stability of the laser beam, which caused the plug to move away from the exact centre and not plug the hole completely.

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 but just moves to a new location where the external field, depending on its strength and direction, cancels the original 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 will never find it! A smooth way to achieve this is to add a rotating field that moves the hole around in a circle. The time-averaged pseudo-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 matter 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. Since the atoms travelled ballistically during the expansion phase, each region of the cloud corresponded to a unique initial velocity, and the spatial distribution of atoms after expansion gave the initial velocity distribution of the trapped atoms. 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 (zero-velocity region), 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. The third feature was particularly convincing, because the trap had different curvatures (or spring constants) in the axial and radial directions, and the velocity distribution of the ground-state atoms reflected this asymmetry.

Soon after this, Ketterle's group solved the beam-pointing problem and 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 several 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

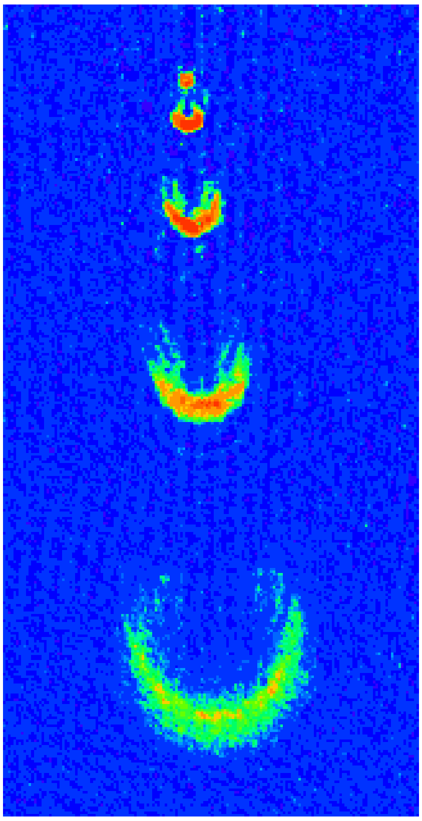

Figure 4. The MIT atom laser. A Bose condensate of sodium atoms (small spot at the top) was trapped between two magnetic field coils by having the magnetic moments of the atoms anti-parallel to the magnetic field. Short pulses of an oscillating magnetic field flipped the magnetic moment of an adjustable fraction of the atoms. These atoms were no longer confined and propagated as a coherent matter wave accelerated by gravity. Every 5 ms, 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. (Courtesy: Wolfgang Ketterle)

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 quite well.

BEC in dilute 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, an Rb BEC was obtained by evaporative cooling in an all-optical trap. The trap is formed using tightly-focused laser beams from a CO_2 laser, 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. A sample list of potential topics includes the study of ultra-cold collisions, collective and particle-like excitations of condensates, vortices, spin systems, mixed fermionic and bosonic systems, etc. 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. This must have been uppermost in the mind of the Nobel Committee when it awarded this year's prize in Physics.

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 succeed in making 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.

For further reading please visit the following websites: http://jilawww.colorado.edu/bec/; http://www.colorado.edu/physics/2000/bec/index.html; http://cua.mit.edu/ketterle_group/

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Biological Weapons Convention—Comatose and barely alive

The Fifth Biological Weapons Convention (BWC) Review Conference convened in Geneva under the aegis of the United Nations collapsed on 7 December 2001. Failing to adopt a final declaration, 144 frustrated States parties to the Convention gave themselves a lollipop: A decision to suspend the conference and reconvene in November 2002.

Six months ago in July, the United States had rejected the outcome of six-and-a-half years of work on a Biological Weapons (BW) protocol, declaring that the 'rolling text' of the protocol was unacceptable to US, and that no amendments could make it acceptable. This decision was widely criticized, including by close allies of the US. However, following the 'anthrax' cases last October–November, heightened concerns on bio-terrorism, and a set of new proposals put forward by the US itself, there was some expectation that this review conference might take a few significant political steps, and agree on some national measures, even if it were not possible to agree to multilaterally negotiated implementation steps that would be legally binding (by treaty) on all States parties.

But the US insisted that the final declaration also include a strong statement on prevalence of non-compliance with BWC by signatory States parties as an established fact, not merely a suspicion. Indeed, US Under-Secretary of State for Arms Control and International Security, John R. Bolton openly named signatory States parties (Iran, Iraq, North Korea and Libya) as producers of BW agents. Other countries were clearly unwilling to accept what delegates from Iran termed (off-conference) 'proofless accusation' that the Convention had thus, by implication, been ineffective.

On other issues before the Review Conference incremental progress led to expectations that the conference would have a positive, even if only a modest outcome. Delegates at the convention were resigned to the inevitable, viz. Given the hard US stance, negotiations (suspended in July) towards an acceptable 'implementation protocol' would not be resumed. However, the mandate agreed to in 1994—'to strengthen the Convention through a legally binding instrument' had not been questioned till the very last afternoon. This mandate could have remained valid awaiting a favourable political environment (like 'sleeping beauty' – in Conference President Hungary's Ambassador Tibor Toth's words – to be awakened by the kiss of a suiting prince-protocol).

India was represented by her experienced Permanent Representative to the UN Conference on Disarmament (UN-CD), Ambassador Rakesh Sood, supported by technical experts from DRDO and ICMR. Sood was joined in the last week of the Conference by a team comprising S. K. Sharma, the physicist–Joint Secretary-in-charge of Disarmament and International Security Affairs in the Ministry of External Affairs, in tandem with the scientist-architect of India's system of control over the export of 'dual-use' materials and equipment pertinent to the development and production of bio-weapons.

India made strenuous efforts to save the Conference. Sood even hosted a lunch on 7 December for all key players, including Bolton, Ambassador Sha Zukang of