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The Nobel Prize in Physics 2001

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2001 jointly to

ERIC A. CORNELL
JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA,

WOLFGANG KETTERLE
Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA, and

CARL E. WIEMAN
JILA and University of Colorado, Boulder, Colorado, USA,

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

New State of Matter Revealed: Bose-Einstein Condensate

A laser beam differs from the light from an ordinary light bulb in several ways. In the laser the light particles all have the same energy and oscillate together. To cause matter also to behave in this controlled way has long been a challenge for researchers. This year's Nobel Laureates have succeeded – they have caused atoms to "sing in unison" – thus discovering a new state of matter, the *Bose-Einstein condensate (BEC)*.

In 1924 the Indian physicist Bose made important theoretical calculations regarding light particles. He sent his results to Einstein who extended the theory to a certain type of atom. Einstein predicted that if a gas of such atoms were cooled to a very low temperature all the atoms would suddenly gather in the lowest possible energy state. The process is similar to when drops of liquid form from a gas, hence the term condensation.

Seventy years were to pass before this year's Nobel Laureates, in 1995, succeeded in achieving this extreme state of matter. Cornell and Wieman then produced a pure condensate of about 2 000 rubidium atoms at 20 nK (nanokelvin), i.e. 0.000 000 02 degrees above absolute zero.

Independently of the work of Cornell and Wieman, Ketterle performed corresponding experiments with sodium atoms. The condensates he managed to produce contained more atoms and could therefore be used to investigate the phenomenon further. Using two separate BECs which were allowed to expand into one another, he obtained very clear interference patterns, i.e. the type of pattern that forms on the surface of water when two stones are thrown in at the same time. This experiment showed that the condensate contained entirely co-ordinated atoms. Ketterle also produced a stream of small "BEC drops" which fell under the force of gravity. This can be considered as a primitive "laser beam" using matter instead of light.

It is interesting to speculate on areas for the application of BEC. The new "control" of matter which this technology involves is going to bring revolutionary applications in such fields as precision measurement and nanotechnology.

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The Nobel Prize in Physics 2001

This year's Nobel Prize in Physics is about an extreme state of matter, the Bose-Einstein Condensate. The three scientists who are awarded the Prize jointly are ***ERIC A. CORNELL****, JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA,* ***WOLFGANG KETTERLE****, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA and* ***CARL E. WIEMAN****, JILA and University of Colorado, Boulder, Colorado, USA. The Royal Swedish Academy of Sciences citation runs "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates". Here we give a background and a description of the contributions of the Laureates.*

New state of matter revealed: Bose-Einstein Condensate

The matter surrounding us consists of atoms that obey the laws of quantum mechanics. At normal temperatures these often agree with classical conceptions, and a gas under these conditions behaves rather like a swarm of billiard balls bouncing against one another and the containing walls. When the temperature is lowered and the speed of the atoms is reduced, however, their properties will be increasingly dominated by the principles of quantum mechanics. The atoms rotate round their axes – they have spin – and this movement is described by a spin quantum number, which has to be an integer – a whole number – or a half-integer. Particles that have integer spin are called *bosons*, while those with half-integer spin are called *fermions*. Bosons show strong "social" behaviour and at low temperatures strive to gather in one and the same quantum state, the one with the lowest energy. Fermions on the other hand avoid one another. They cannot appear in exactly the same quantum state, so that states of higher energy must also be used. The arrangement of the elements in the periodic system may be understood on the basis of the fact that the electrons in the atomic shells are fermions.

As early as 1924 the Indian physicist S.N. Bose carried out a statistical calculation for the kind of particles which have since come to bear his name, bosons, and more specifically light particles later termed photons. Bose presented an alternative derivation for the radiation law earlier found by Planck. Bose sent his work to A. Einstein, who realised its importance. He translated it to German and had it published. Einstein rapidly extended the theory to cover Bose particles with mass and he himself published two articles in quick succession, predicting that when a given number of particles approach each other sufficiently closely and move sufficiently slowly they will together convert to the lowest energy state: what we now term *Bose-Einstein condensation (BEC)* occurs.

Ever since publication of this pioneering work, physicists have wished to be able to achieve this new fundamental state of matter, which was expected to have many interesting and useful properties. Seventy years were to pass before this year's Laureates, **Eric A. Cornell, Wolfgang Ketterle** and **Carl E. Wieman**, using very advanced methods, finally managed to do this in 1995. The state was achieved in alkali atom gases, in which the phenomenon can be studied in a very pure manner. Nowhere else in the universe can one find the extreme conditions which BEC in dilute gases represents. Manifestations of Bose-Einstein condensation have earlier been observed in more complicated systems: condensation of paired electrons in superconductors (loss of all electrical resistance) and suprafluidity (loss of internal friction in fluids). Here, too, low temperatures are required. Research in these areas has been rewarded with several Nobel Prizes. As opposed to alkali-atom vapours these quantum-mechanical systems are not simple since the condensation phenomenon concerns only a part of the systems and the strong interactions involved tend to hide the BEC phenomenon.

Waves or particles?

According to the laws of quantum mechanics that govern conditions in the microcosmos, what we normally term a particle can sometimes behave like a wave. This is well known and is used in e.g. the electron microscope. As early as 1924 L. de Broglie postulated the existence of matter waves and expressed their wavelength λ in terms of the of momentum of the particles p:

$$\lambda = h/p$$

where h is Planck's constant. The more slowly the particle moves the less its momentum and the longer the de Broglie wavelength. According to the kinetic theory of gases low particle velocities correspond to low temperatures. If a sufficiently dense gas of cold atoms can be produced, the matter wavelengths of the particles will be of the same order of magnitude as the distance between them. It is at that point that the different waves of matter can 'sense' one another and co-ordinate their state, and this is Bose-Einstein condensation. It is sometimes said that a "superatom" arises since the whole complex is described by one single wave function exactly as in a single atom. We can also speak of *coherent matter* in the same way as of *coherent light* in the case of a laser.

Gases when cooled generally condense into liquids. This must be avoided and, as this year's Nobel Laureates have shown, this is possible with alkali atoms. For rubidium with mass number 87, ^{87}Rb, and sodium with its single stable isotope ^{23}Na, which both have integer atomic spin, weak repulsive forces arise between the atoms in each case. It can be shown that BEC occurs if the density, expressed as the number of atoms in a λ-sided cube exceeds 2.6. It can then be calculated that the atoms for realistic densities must move very slowly, at speeds of the order of a few millimetres per second. This corresponds to temperatures of the order of 100 nK (nanokelvin), i.e. a tenth of a millionth of a degree above absolute zero. This year's Nobel Laureates achieved this by using in a decisive manner the methods of cooling and trapping neutral atoms for which the Nobel Prize in Physics was awarded in 1997 (S. Chu, C. Cohen-Tannoudji and W.D. Phillips).

Laser cooling and evaporative cooling lead to BEC

Laser cooling of neutral atoms was proposed in 1975 by T.W. Hänsch and A.L. Schawlow. The basic principle is to exchange momentum between photons and atoms. Cooling is achieved by arranging that the photons can be absorbed only if they collide head-on with the atom in its flight. The speed is then reduced, primarily to a limit set by the randomness course of spontaneous emission. The 1997 Nobel Laureates showed that what is termed the Doppler limit can be overcome using refined processes, so that considerably lower temperatures can be achieved. However the cloud of cooled atoms must also be held together, and this can take place in what are termed atom traps. These often work on a combination of laser beams and magnetic fields. The magneto-optical trap (MOT) has become specially important. Several research groups have used this technique for approaching BEC conditions. However a further cooling technique proved necessary, *evaporative cooling*, which was employed in D. Kleppner's and T.J. Greytak's group at MIT. Here the medium is cooled by ensuring that the fastest atoms leave the community. The average temperature among those remaining then is reduced. The coffee in a cup cools in a similar fashion! In an atom trap the atoms are kept in place by magnetic dipole forces. The attractive force can be turned into a repelling force if the atomic magnetic poles are reversed. This can be achieved with a radio-frequency field, an effective method proposed by D.E. Pritchard at MIT. The most rapid atoms move high up at the edge of the potential well, where the magnetic field and hence the conversion frequency for pole switching is high. By initially applying a high frequency and then gradually lowering it, it is possible to successively skim off the hot atoms. In this way the JILA* group, led by Cornell and Wieman, managed, in June 1995, for the first time, to achieve a condensation limit in ^{87}Rb. A final difficulty to overcome was to avoid atom loss at the centre of the trap, where the magnetic field is zero and spontaneous pole-switching is possible. By rotating a magnetic field sufficiently rapidly over the sample, it was possible to prevent the atoms from systematically pouring out of the trap.

Around 1990 Wieman drew up guidelines for how BEC could be achieved in alkali atoms. Important aspects were laser cooling in a MOT and transfer to a purely magnetic trap in which evaporative cooling could then be applied. Cornell was hired by Wieman to work on the project, initially as a "postdoc", but was soon permanently employed at NIST. In the JILA experiments, the spectacular results of which are illustrated in Figure 1, the process was initiated at a temperature of approximately 170 nK. By making the evaporative cooling more effective a pure condensate was obtained with a temperature of 20 nK. About 2 000 atoms then remained in the sample.

The images shown in the figure were obtained by suddenly switching off the confining forces in the trap, whereupon the cloud expands, more and more slowly the colder the atoms are. A silhouette image of the cloud was made using resonant laser light after a predetermined delay and the temperature was calculated on the basis of the size the cloud had achieved during this period. The figure shows atomic distributions calculated from shadow images.

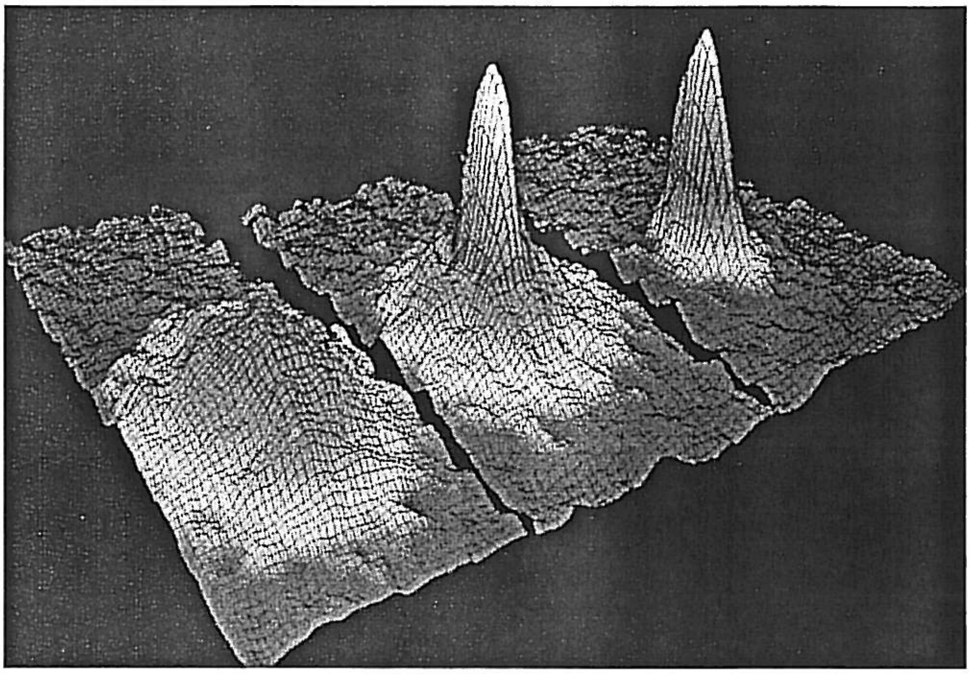

Figure 1. Successive occurrence of Bose-Einstein condensation in rubidium. From left to right is shown the atomic distribution in the cloud just prior to condensation, at the start of condensation and after full condensation. High peaks correspond to a large number of atoms. Silhouettes of the expanding atom cloud were recorded 6 ms after switching off the confining forces of the atom trap.

** JILA is a joint research institute for NIST (National Institute of Standards and Technology) and University of Colorado. It was earlier called Joint Institute for Laboratory Astrophysics. Today only the abbreviation JILA is used.*

Ketterle worked independently of the Colorado group using sodium atoms which absorb and emit yellow light. He came from Germany in 1990 as a postdoc to D. Pritchard's group at MIT and assumed main responsibility for the BEC project in 1993. Ketterle solved the problem of atom losses at the centre of the trap by focusing there a powerful laser beam which kept the atoms away from the loss area. He published his BEC results for sodium only four months after the publication of the JILA group. Ketterle showed recordings similar to those shown in figure 1 but now with many more atoms in the condensate. Since there were now many hundred times more atoms to work with, it became possible to make spectacular measurements of the properties of the condensate. It was shown for example that two separate condensates, if allowed to expand into each other, exhibit very clear interference effects (figure 2), indicating the coherence of matter waves and long-range correlation. Ketterle also demonstrated how parts of the condensate could be successively switched out in 'BEC drops' that fall in the field of gravity (figure 3). The phenomenon has been described as an atom laser of coherent matter.

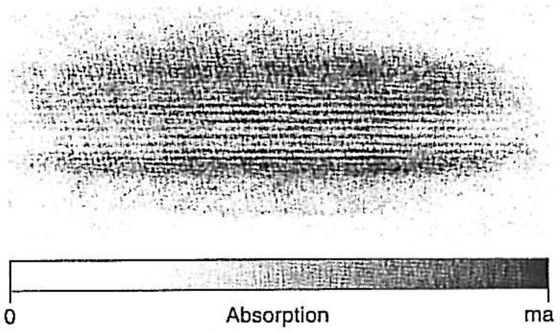

Figure 2. Pattern of interference between two overlapping Bose-Einstein condensates of sodium atoms. The image was made in absorption. Matter-wave interferences have a periodicity of 15 micrometer. The recording shows that the atoms of the two condensates were fully co-ordinated.

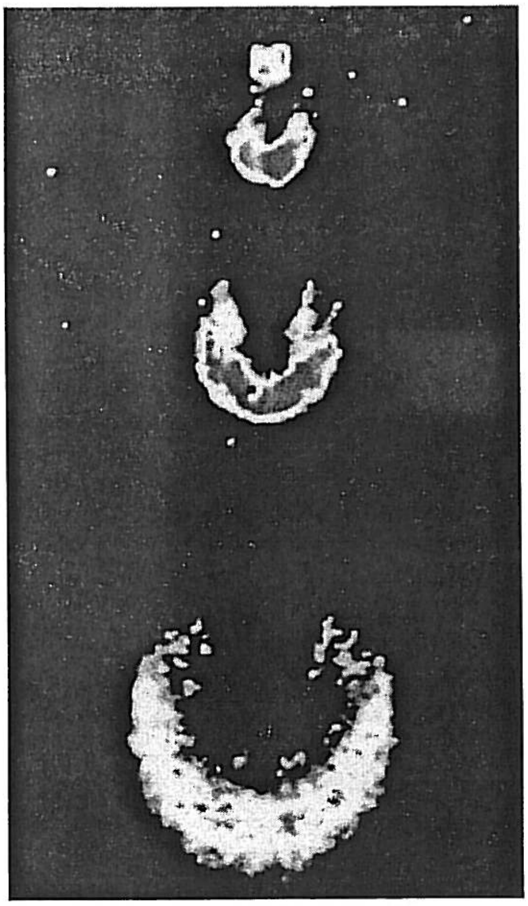

Figure 3. Repeated release from the trap of parts of a Bose-Einstein condensate of sodium atoms. Pulses of coherent matter fall in the gravitational field – the phenomenon can be seen as an atom laser effect. The real size of the picture is 2.5 mm X 5 mm.

The BEC field is developing explosively

Following the very spectacular demonstrations of BEC in rubidium and sodium by the JILA and MIT groups, the field has developed explosively and over 20 groups are now conducting BEC experiments. Of particular mention are the activities in R.G. Hulet's group at Rice University. There, work has been carried out with the lithium isotope ^{7}Li, for which attractive forces occur when two atoms approach one another, as opposed to the case for ^{87}Rb and ^{23}Na. In a 1997 publication, the group showed clearly that a small condensate of about 1000 atoms was obtained, exactly as predicted by the theory. That the cloud does not collapse in molecule aggregation under the influence of the attractive forces is because of energy fluctuations of the atoms in the trap.

Though a very large number of groups have entered the field, Cornell's, Wieman's and Ketterle's groups have maintained their lead, and many interesting new results have been presented. The JILA group has studied, for example, collective excitations and vortex formations in condensates. The Ketterle group has developed an improved method for imaging the condensate, which remains uninfluenced by the measurement so that it can be re-measured many times. Magnetic-field-dependent resonances have also been observed in the forces between the atoms, and these strongly influence the properties of the condensate. In addition, the group has demonstrated that an atom laser beam can be amplified analogously with a laser beam. W.D. Phillips' group at NIST in Maryland is also among those that have presented fundamental results, demonstrating among other things a phenomenon that corresponds to four-wave mixing of non-linear optics using matter waves.

The experimental search for BEC in dilute gases started early with the use of spin-polarised hydrogen in Kleppner's and Greytak's group at MIT but it turned out to be very hard to achieve the appropiate conditions. Eventually, however, more than three years after the JILA group's first article, BEC results were published for hydrogen. D. Kleppner has meant much, among other things as a source of inspiration, in the race for BEC. BEC has recently been developed to cover further types of atoms through two groups in Paris, who have reported condensation in meta-stable helium atoms.

Prospects

Bose-Einstein condensation in dilute gases offers particularly rich possibilities for studies of fundamental quantum-mechanical processes. Extremely comprehensive research activity, both experimental and theoretical, is going on in the field, including studies of non-linear processes and manipulation of the speed at which light propagates. The influence on other research areas is also great. Recently the JILA group has demonstrated that with ^{85}Rb it is possible using the above-mentioned resonances to switch rapidly between attractive and repulsive atomic forces, leading to dissolution of the condensate that resembles that of a supernova (the "Bose-nova"). Studies of phenomena related to BEC for fermions at extremely low temperatures by D. Jin and co-workers at JILA are revealing new aspects of the statistical conditions in physical systems, indicating future possibilities of observing atomic pair-formation and suprafluidity properties. R.G. Hulet's group has shown that an outward pressure arises because of the repulsive nature of fermions in a degenerate atomic Fermi gas, and that conditions resembling those in white dwarf stars can be simulated.

It will be possible to exploit the BEC phenomenon in gases in precision measurements of fundamental natural phenomena where sharp resonances in essentially motionless atoms or sharp matter-interference fringes are used. Revolutionary applications of BEC in lithography, nanotechnology and holography appear to be just round the corner.

FURTHER READING

Website with animations, questions and answers etc.: www.colorado.edu/physics/2000/bec
The websites of the Laureates, see below.
Advanced information on the Nobel Prize in Physics 2001, The Royal Swedish Academy of Sciences
Internet: http://www.nobel.se/physics/laureates/2001/phyadv.pdf
The Bose-Einstein Condensate by E.A. Cornell and C.E. Wieman, Scientific American, March 1998, p. 26.
Bose-Einstein Condensation by Ch. Townsend, W. Ketterle and S. Stringari, Physics World, March 1997, p. 29.
Experimental Studies of Bose-Einstein Condensation by D.S. Durfee and W. Ketterle, Optics Express Vol. 2, p. 299, 1998, also available on Internet http://epubs.osa.org/opticsexpress (with animations)
Bose-Einstein Condensation, edited by A. Griffin, D.W. Snoke and A. Stringari, Cambridge University Press, 1995.
Kylning och infångning av neutrala atomer med hjälp av laserljus, av S. Svanberg, *KOSMOS* 1998, sid. 7.

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