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Advanced information on the Nobel Prize in Physics 2001

Bose-Einstein Condensation in Alkali Gases

1. Bose-Einstein Condensation

At the beginning of the twentieth century, the quantum nature of thermal electromagnetic radiation was a subject of intense interest. This was sparked by Max Planck's discovery that the spectral distribution of light emerging from a thermal body could be explained only if the radiators emitting the energy occurred in discrete energy states. This induced Albert Einstein to conclude in 1905 that it was the radiation itself that was created and converted in bursts of energy; these bursts are light quanta. They were later to be called photons. The vision of such discrete energy packets travelling through space suggested to Einstein several physical consequences. In addition to rederiving Planck's result, Einstein discussed: frequency conversion (later related to the Raman effect), ionisation of atoms by light, and the emission of electrons from illuminated metal surfaces. The last discussion gives the theoretical description of the photoelectric effect, for which Einstein was in 1922 awarded the 1921 Nobel Prize.

In 1924 the physicist S. N. Bose from Dacca University in India sent Einstein a paper, in which the Planck distribution law for photons was derived by entirely statistical arguments [1] without resort to results from classical electrodynamics. Einstein realized the importance of the paper, translated it into German and submitted it for publication in *Zeitschrift für Physik*. He immediately started to work on the problem himself, and published two papers in 1924 and 1925 [2], developing the full picture of the quantum theory of bosonic particles. So fast did the development of physics proceed even in those days. The concept of particles obeying Bose-Einstein statistics was born, and today we know that all entities with an integer spin value will display the total symmetry characterizing this statistics.

Einstein noted that if the number of particles is conserved, even totally noninteracting particles will undergo a phase transition at low enough temperatures. This transition is termed Bose-Einstein condensation (BEC). Bose did not find this feature because he was discussing photons which, being massless, do not need to condense, because they can disappear instead when the energy of the system is decreased.

The condensation Einstein found derives from the fact that, in the limit of an infinite three-dimensional volume, the total number of states at vanishing energy becomes exceedingly small. Thus there is not room for all the particles when the temperature is decreased, and the system can only accumulate all the superfluous particles in its very ground state; they condense into the lowest energy state. In the thermodynamic limit, when both the particle number and the volume grow to infinity, the system enters into a different state, thus undergoing a phase transition. For a long time, no physical system was known which would display this interesting phenomenon.

The liquid phase of the helium isotope ^{4}He had early been found to present perplexing superfluid behaviour. This was noted, e.g., by H. Kamerlingh Onnes, who had received the Nobel Prize in physics 1913. Eventually, in 1938 F. London suggested that superfluidity could be a manifestation of bosonic condensation of the helium atoms. This suggestion was supported by the fact that no similar effect was seen in the isotope ^{3}He , which represents Fermi-Dirac statistical behaviour. However, for a long time it was difficult to connect this to the physical properties of the fluid. Then in the 1950s, O. Penrose and L. Onsager related superfluidity to the long-range order displayed by a highly correlated bosonic system. This allowed them to derive an estimate of the amount of condensed atoms in the liquid. They found only 8 %, which is because the strong interactions in liquid helium make it deviate significantly from the ideal noninteracting gas. The superfluid transition occurring at the temperature of 2.17 K, however, still somehow seems to be related to the condensation discovered by Einstein.

The strong interaction in liquid helium has prevented all *ab initio* computations of its properties even up to the present time. Its most striking feature was the ability to flow without resistance, as if no internal frictional forces acted in the liquid. This superfluidity was, however, explained by a phenomenological theory devised by L. D. Landau in 1941. In 1962 he was awarded the Nobel Prize in physics for this work. In Landau’s theory, superfluidity derives from the fact that, when the available energy is low enough, only long-wavelength phonons can be excited. For a weak interparticle interaction, N. N. Bogoliubov in 1947 derived the low-energy phonon spectrum by assuming that the dynamic behaviour is dominated by the atoms constituting the condensate. This work introduced the Bogoliubov transformation, which has later been extremely useful in many systems: superconductivity, nuclear physics, and the more recent atomic condensates.

The weakly interacting system was treated in perturbation theory by K. Huang and his collaborators, who in the 1950s managed to obtain a good understanding of the structure of the perturbative ground state. This was followed by an extensive many-body effort to describe the more strongly interacting helium system in the 1960s, but after this there has been little theoretical progress until recently.

Closely related to the frictionless flow of a superfluid is the resistanceless current flow in certain metals at low enough temperatures. This was discovered by H. Kamerlingh Onnes in 1911, but reaching a full theoretical explanation took nearly 50 years. This was based on two approaches: J. Bardeen, L. N. Cooper and J. R. Schrieffer in 1957 derived a microscopic theory based on phonon-mediated interactions between the electrons of the metal. This work gave them the Nobel Prize in physics in 1972. V. L. Ginsburg and L. D. Landau had already in 1950 suggested a phenomenological theory, but the useful applications of this approach emerged only slowly.

The microscopic theory showed that superconductivity is based on the fact that electrons of opposite spin acquire strong correlations, which make them enter a highly coherent state which is insensitive to perturbations, hence the lack of electric resistance. As individual electrons obey Fermi-Dirac statistics, their pairs can be considered as analogues of bosonic particles, and the superconductivity transition is similar to Bose-Einstein condensation.

The phenomenological theory, on the other hand, carries little signature of its microscopic origin, but the theory has turned out to be eminently suitable to describe the physics of space- and time-dependent superconductivity. The Ginsburg-Landau equation has been extremely useful and it has been widely utilized to discuss applications of superconductivity.

The fermionic helium isotope ^{3}He undergoes at 3 mK a phase transition analogous to superconductivity. Like the conduction electrons, the helium atoms pair up to bosonic entities, which enter a condensed state. This phase was first observed by D. M. Lee, D. D. Osheroff and R. Richardson in 1972, and this discovery merited them for the Nobel Prize in physics in 1996. In liquid helium, however, the strong particle repulsion makes the atoms join with a unit value of both total spin and total angular momentum. This makes the condensate structure very complicated, and leads to a wide variety of possible phases. Correspondingly the system displays a multitude of phenomena, which have been extensively investigated. In the theoretical research both the microscopic approach and the phenomenological Ginsburg-Landau theory have been generalized to provide a good understanding of the situation.

2. Cooling and Trapping of Atomic Species

In the 1960s, the laser developed into a scientifically interesting physical system and a powerful tool for investigating new phenomena. The high intensity and excellent directionality of the laser beam offered an energy and momentum density not achievable with conventional light sources. It thus became clear that laser light could be used to affect the mechanical behaviour of atomic motion. Atomic beam deflection had been known ever since Maxwell derived an expression for the light pressure of radiation, and it had even been observed experimentally with conventional light sources. With lasers, the effects were expected to become more spectacular. V. S. Letokhov suggested atomic trapping with electromagnetic fields in 1968, and in 1970 A. Ashkin derived the light pressure force on an atom in resonance with the light beam. During the 1970s, it became obvious that the mechanical manifestations of laser light would imply many interesting physical effects.

T. W. Hänsch and A. L. Schawlow recognized in 1975 that laser light could be used to cool free atoms. This is because an atom absorbing a photon must also accommodate its momentum. If the conditions are right, this can slow down the atom. A subsequent spontaneous emission carries momentum irreversibly into an arbitrary direction leaving the atom on the average with decreased velocity. Thus cooling ensues. By utilizing the Doppler shift, atoms can be made to always absorb photons from their forward direction. Thus a suitable three-dimensional laser configuration can cool all degrees of freedom. In this so called Doppler cooling the ultimate energy limit is set by the random process of spontaneous emission.

The first successful experiments on laser cooling were performed by V. I. Balykin and V. S. Letokhov in Moscow and W. D. Phillips and his collaborators at Gaithersburg around 1980. Further developments were rapidly forthcoming, and W. D. Phillips, S. Chu and C. Cohen-Tannoudji developed methods to cool below the naively obtained Doppler limit of earlier theories.

The light traps evolved at the same time. Early Chu and his collaborators at Bell Laboratories trapped slow atoms into a purely optical field using its ponderomotive potential. This trap was filled by atoms cooled in a three-dimensional laser configuration called “optical molasses”. Purely optical traps are, however, very weak and small, and better traps were needed to accumulate physically interesting numbers of atoms. The Gaithersburg group under Phillips used magnetic fields for trapping, but only a combination of magnetic field gradients with Zeeman tuning of the photon absorption offered a trap efficient enough to become a standard tool for future work. Such a magneto-optical trap (MOT) was originally suggested by J. Dalibard from Paris in 1986, but it was taken up and developed by D. E. Pritchard’s group in collaboration with Chu. This trap has been of the utmost importance for further developments. It combines trapping and cooling, it has a large range for capturing atoms, and they are strongly confined.

The highly sophisticated experimental methods S. Chu, C. Cohen-Tannoudji and W. D. Phillips developed made laser cooling and trapping a useful tool for further experimental progress. For these achievements they were in 1997 awarded the Nobel Prize in physics.

Later other magnetic configurations have been developed: Pritchard and collaborators combined a quadrupole field with an axial bias field to utilize a configuration earlier discussed by Ioffe in 1962.

3. Search for BEC in Atomic Hydrogen

It was early clear that great physical interest would arise if BEC could be achieved in a dilute system of atomic particles. The conditions needed are, however, rather formidable. In order to “see each other” the atomic wave functions must be extended enough to have appreciable overlap. The minimum size of the wave function is given by the thermal de Broglie wavelength, which has to be larger than the interparticle spacing to allow the quantum statistics of the particles to exert an effect. This implies low energies (i.e. low temperatures) and large particle densities. Most atomic species are likely to form molecules or condense into a liquid in this situation. The challenge is thus to achieve the desired atomic density while retaining the atomic gas intact.

In 1976 L. H. Nosanow and W. C. Stwalley [3] suggested that spin-polarized atomic hydrogen would retain its gaseous state down to arbitrarily low temperature. The single fermionic proton and electron combine to form the spin states zero and one. As the hydrogen molecule has an electronic spin, zero ground state (singlet), a gas of atoms, all with the same total spin cannot combine to form molecules except in three-body collisions. Thus a gas of stable bosonic particles could be achieved. Experiments were initiated at MIT by D. Kleppner and T. J. Greytak and in Amsterdam by I. F. Silvera and J. T. M. Walraven. To reach the necessary low energy, evaporative cooling was suggested by H. F. Hess in 1986 [4]. This is a method where the most energetic atoms are allowed to escape the trap, thus leaving the remaining ones at a lower effective temperature. This is the process that cools a cup of hot tea.

Many unsuccessful attempts were made to achieve BEC in spin-polarized hydrogen, even though both evaporative cooling and magnetic trapping were demonstrated. This left the physics community frustrated.

4. Achieving BEC in Alkali Atoms

After all attempts to reach the particle densities necessary for BEC in hydrogen, some new approach was needed. During this work, the technology of laser cooling had made great progress and contributed a new experimental tool. This was, however, not very useful for hydrogen, because the strong Lyman-α lines at wavelength 121.6 nm were not in resonance with any convenient laser source. Instead interest turned to alkali atoms. Their single valence electron combines with nuclei that have odd spin quantum numbers to hyperfine levels with integer angular momentum, thus providing many isotopes with bosonic character.

C. E. Wieman at JILA in Boulder started a program of this kind, and he correctly envisaged the steps necessary to reach conditions favoring the formation of BEC [5, 6]. The road he suggested turned out to be essentially the one eventually leading to success.

Wieman’s idea was to laser cool the atoms in a MOT trap, transfer them into a purely magnetic trap and continue the process by evaporative cooling down to the necessary low temperatures. In pursuing these goals Wieman hired E. A. Cornell as a Post Doc. Cornell was soon appointed as a scientist at NIST in Boulder and the two researchers continued the work along two slightly different routes, both, however, applying the same basic ideas and using rubidium atoms.

The atoms that are to condense have to be in identical spin states. Thus spin flips tend to counteract the success of the process. In a magnetic trap, the field vanishes at the center of the trap, which allows the spin state to change in an uncontrolled way (so-called Majorana flips). To prevent this mechanism from causing loss of atoms, Cornell developed a configuration with a rotating magnetic field, which averaged the trap potential and eliminated the region where it vanishes [7]. This time-orbiting potential (TOP) configuration proved efficient, and led to successful formation of BEC in ^{87}Rb in June 1995 [8]. Prior to the successful experiments, much discussion was devoted to the question of an unambiguous signature for the presence of BEC. When the breakthrough came, no doubts remained: as can be seen from Fig.1, the appearance of a central condensed atomic cloud is manifest. Much work, however, remained to be done. Cornell and Wieman continued to work together conducting many of the fundamental investigations into the physical properties of the BEC system (see below).

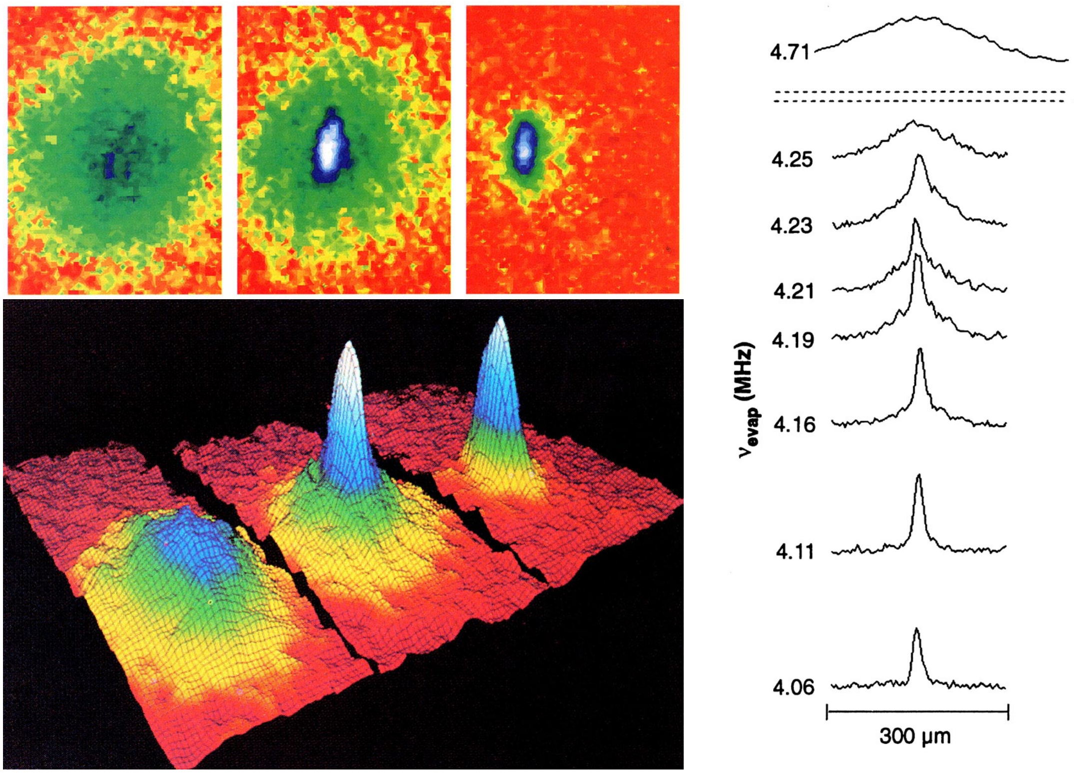

Figure 1: Observation of BEC in rubidium by the JILA group. The upper left sequence of pictures shows the shadow created by absorption in the expanding atomic cloud released from the trap. Below, the same data are shown in another representation, where the distribution of the atoms in the cloud is depicted. In the first frame to the left, we see the situation just before the condensation sets in, in the middle a condensate peak with a thermal background is observed, whereas the third figure shows the situation where almost all atoms participate in the condensate. The thermal cloud is seen as a spherically symmetric broad background, whereas the sharp peak describing the condensate displays the squeezed shape expected in an asymmetric trap. The diagram to the right cuts through the atomic cloud when it is cooled by more and more atoms being evaporated. The figures are from publication [8].

The experimental recordings are made by releasing the atomic cloud from the trap and imaging its later shape by the shadow formed with resonant light. It will then have expanded and takes up a larger shape mainly determined by its momentum distribution at the moment of release. The pedestal seen in the figure derives from the thermal cloud, which is essentially spherically symmetric, whereas the condensate peak mirrors the asymmetry of the condensate wave function in the momentum representation. The fact that its image is not symmetric constitutes strong evidence for the presence of BEC. Since the detection method is destructive, the experiment requires good reproducibility.

Many of the basic ideas used to achieve BEC had been developed at MIT by the groups around D. Kleppner and D. E. Pritchard. W. Ketterle joined this effort in the early 1990s, and he became the senior investigator in the experimental program to achieve BEC. He chose to work with ^{23}Na, and avoided the central trap region with a vanishing magnetic field by plugging it with a strongly repulsive laser beam [9].

Ketterle's MIT work proved successful only a few months after the Boulder experiments, and its publication is dated only about four months later [10]. The evidence is just as spectacular as that in Boulder as seen in Fig. 2. In addition to providing a new system displaying BEC, the MIT experiment contained considerably more atoms, by a factor of more than two orders of magnitude. This proved to be a significant advance in the possibilities to explore the physical characteristics of the condensate. In this effort both the Boulder and the MIT group contributed within a short period after these initial successes (see below).

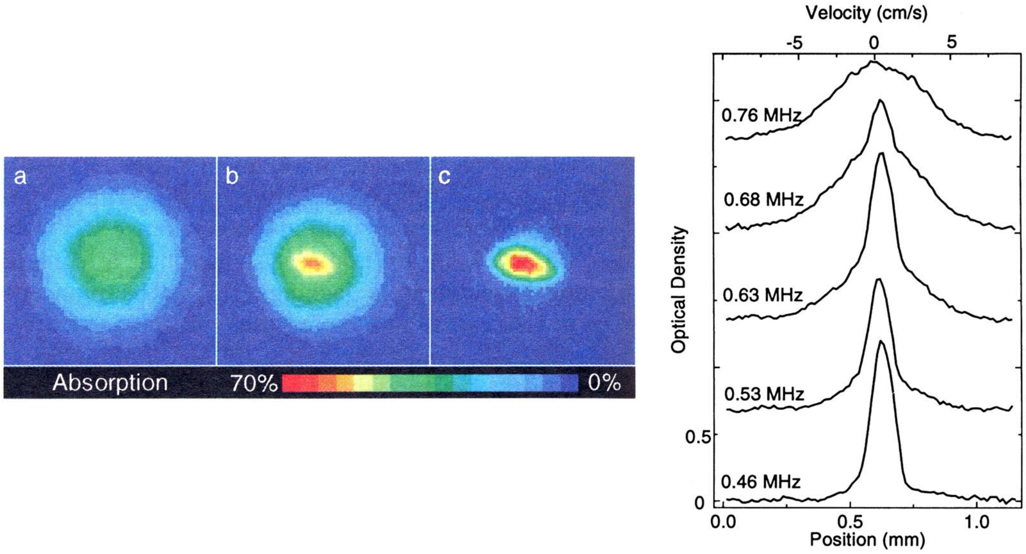

Figure 2: Observations of BEC in sodium atoms achieved in the MIT group. These pictures are obtained as those presented in Fig. 1. The left-hand side shows shadow images as in Figure 1, where the density of the condensate is seen to grow with decreasing temperature from left to right. The right-hand diagrams show cuts through the density as the condensate developes. The figure is from publication [10].

5. Other Physical Systems

Concurrently with work in Boulder and at MIT, R. G. Hulet at Rice University, Houston Texas, worked on trapping and cooling ^{7}Li in order to achieve BEC. This effort was started early, but unambiguous results were published only in 1997 [11] after some initial inconclusive results obtained by the group in 1995.

The case of lithium atoms is an interesting complement to the work on rubidium and sodium. This derives from its different interaction between individual atoms. As pointed out, at the temperatures where BEC can occur, the atomic wave function must extend over more than the interparticle separation. Thus the wave function involves only wavelengths unable to resolve the detailed structure of the interatomic potential whose extension is much less than the interparticle spacing. The interaction can consequently be characterized by one single parameter, conventionally chosen to be a length, termed the scattering length. If this is positive, the atoms experience mutual repulsion, if it is negative they attract each other. In rubidium and sodium we have repulsion but in lithium we have attraction. The latter system tends to collapse at too high densities. Thus arose the question whether BEC could be achieved at all in such systems. Theoretical estimates indicated that only about 1400 atoms could possibly condense, and indeed the successful experiments by Hulet involved no more than about 1000 atoms, in agreement with theory. Confined to the trap volume, the quantum mechanical wave function can stand against the attractive interatomic forces for so few particles.

After a long period of frustration, also the hydrogen work under Kleppner and Greytak lead to results in 1998 [12]. The goal was achieved by further development of the evaporation technique, which produced a long and slender condensate containing a large number of atoms ($\sim 10^9$). The existence of the condensate can only be inferred by indirect observations; no imaging is possible.

As already mentioned, the superfluidity of liquid helium is a manifestation of the Bose character of its strongly interacting particles. At Cornell University in 1983, J. D. Reppy published the results of experiments on helium confined within a porous substance, Vycor glass [13]. The observation reports superfluid properties which indicate BEC behaviour when the degree of helium coverage was varied. Close to the transition point, the measurements agree with the behaviour in the bulk liquid, which suggests the presence of BEC despite the confinement to a random medium. However, the evidence is rather indirect and the influence of the glass is hard to evaluate theoretically; hence these observations have not led to further progress.

Exciton formation offers another system where bosonic condensation has been suggested on the basis of experimental evidence. The charge carriers in semiconductor materials consist of quasiparticles referred to as electrons and holes. These being of opposite charge, they can be expected to form bound states analogous with hydrogen and positronium. A naive picture would describe these as simple bosonic entities which could condense like other bosons. The detailed theoretical picture is, however, more complex. Such quasiparticles are elementary excitations in a complicated many-body system, and their strongly correlated states are really resonances in their mutual scattering behaviour. Consequently any collective behaviour such as condensation is a complex many-body effect very far from the ideal gas case envisaged by Einstein.

The possibility that actual exciton condensation occurs in semiconductor systems offers an interesting challenge to condensed matter physics. However, even full experimental confirmation of such a phase transition will not constitute a phenomenon of the same type as BEC in alkali atoms, for which the physical situation is very clear-cut.

6. The Physics of BEC in Atomic Condensates

A large theoretical effort followed the initial success of the experiments on trapped alkali atoms. In contrast to the situation in liquid helium, these dilute gas systems are well described by existing theories. The equation Ginsburg and Landau derived for superconductors has an analogue in the case of condensed bosons. Called the Gross-Pitaevski equation, it affords an excellent description of the newly-found condensates of alkali atoms. Many physical properties have been derived and interesting physical features have been predicted for the novel systems. To achieve the realization of BEC was not enough; an extended experimental effort was needed to establish the correctness and relevance of the physical understanding of the phenomenon. Here the work by Cornell, Wieman and Ketterle proved decisive, their large body of experimental investigations thus verifying many of the remarkable physical properties displayed by the macroscopic quantum state of BEC. Some of these will be described briefly here.

The Bose-Einstein condensate consisting of alkali atoms is still far from the original free-particle case investigated by Einstein. Firstly, the particles are trapped in a finite region, with only a finite number of particles not an infinite assembly. Thus no really thermodynamically singular phase transition is possible; however, when millions of atoms are involved, this matters little. The system undergoes a transition of its state which clearly displays the experimental signature of a genuine phase transition. The more important feature is that, even if dilute, the system is far from weakly coupled. The atoms are confined to a trap characterized by its vibrational energy quanta. In the physical systems, the average particle-particle interaction energy is about an order of magnitude larger than the trap quanta. Thus about ten vibrational quantum states are needed to build up the wave function of the condensate, which implies that it is considerably more extended than the non-interacting ground state wave function in the potential. A consistent picture of the situation can, however, be obtained if we assume that all condensed atoms are in a state which is determined self-consistently by the interaction and the trap potential. This picture works even in the dynamic case when the condensate is perturbed and its excitations investigated. Such a theoretical description turns out to be equivalent with the approach based on the Gross-Pitaevski equation.

In a non-interacting gas, the particles do not influence each other, they only occupy the same single-particle state. The effect is thus a pure population effect, in this aspect similar to the thermal distribution of photons. On the other hand, in the trapped gases, the interaction tends to correlate the particles in a manner similar to the coherence of induced photons in a working laser. Thus the condensate is expected to display long-range correlations through the sample and phase coherence between its different parts. These properties give rise to various physical effects which had to be observed if our theoretical picture was to be verified. In the early experimental effort, the contribution by Cornell, Wieman and Ketterle played a central and decisive role.

The theoretical calculations gave very definite predictions for the elementary excitations of the trapped condensate. These were verified by the Boulder group of Cornell and Wieman in good agreement with theory at low enough temperatures. At the transition point, the situation is more difficult to understand. At Boulder the phenomenon of sympathetic cooling was also demonstrated. This is the process whereby two separate condensates are formed by cooling only the one species; the other is cooled by collisional transfer of energy between the two. Thus two partly overlapping condensates have been obtained.

The MIT group under Ketterle developed an imaging method based on non-resonant light, which allows non-destructive probing of the condensate. This allows also direct dynamic observation of time-dependent processes. The phase coherence of the condensate is a property of essential significance for the physics of BEC. By separating the condensate into two parts, Ketterle observed interference fringes between them, Fig.3, which shows that they remain phase coherent even after separation [14].

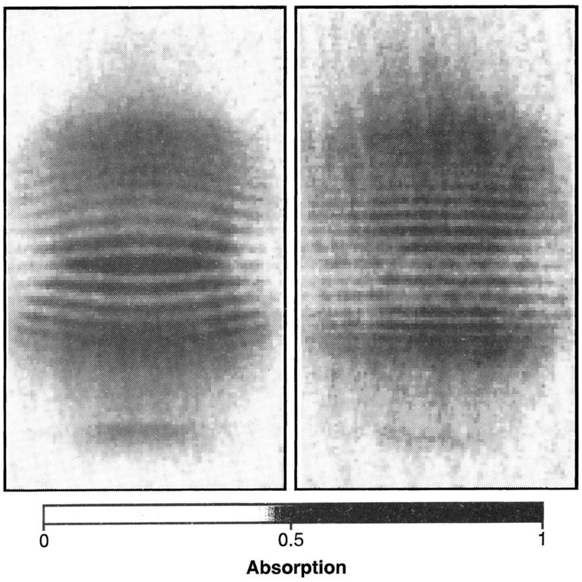

Figure 3: Two examples of the appearance of interference fringes between two separated parts of a condensate. This figure is taken from publication [14] by the MIT group. A condensate is first divided into two parts and subsequently released to fall under the influence of gravity. The two coherent atomic clouds expand into each other, and because they retain their coherence from the original condensate, they display interference where their densities overlap. This is a significant signature of condensate coherence.

To use the coherent atomic clouds, one has to transfer them out of the trap without destroying their quantum nature. Ketterle showed that one can couple out blobs of atoms from the condensate in the form of the bursts seen in Fig. 4 [15]. This effect has been called an “atomic laser” but no induced emission of atoms does, of course, take place. The atoms are correlated in the condensate, and they are released while retaining their coherence. The analogue is the pulsed release of photons from an operating laser, i.e. repeated Q-switching.

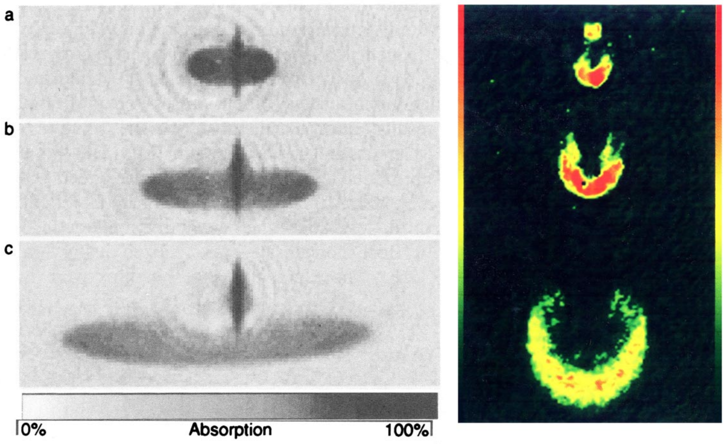

Figure 4: Coherent emission of condensed atoms from a trap as observed by the MIT group. The left-hand picture from the publication [15] shows the original condensate as a vertical structure; the consecutive pictures show how the atoms are emitted in blobs, when they are released by the application of an out-coupling electromagnetic pulse. They are seen to fall in the gravitational field and spread. The later picture to the right shows another sequence of out-coupled pulses. This is a demonstration of the "atom laser action" of a Bose-Einstein condensate.

We noted above that atomic interaction can be characterized by a single parameter of dimension length. This can, however, be affected by subjecting the atom to a magnetic field. States very close to forming molecules from cooled atoms are very sensitive to magnetic fields. Using this feature one can change the character of the interaction, which offers the intriguing possibility to change its sign during the experiment through such Feshbach resonances. This possibility is currently of central interest and was first investigated experimentally in a condensate by Ketterle. He has also studied the dynamic formation and destruction of the condensate, the critical velocity of a condensate, and its domain structure analogous to the magnetic properties of solids.

A consequence of long-range coherence in a condensate, which has played a central role in the physics of liquid helium, is the appearance of vortex structures. The quantum character of the single-particle wave function imposes quantization conditions on the amount of rotation possible, and this can manifest itself in vortex structures also in atomic BEC. Such structures were first observed in the Cornell and Wieman group, and they have recently been investigated also by Ketterle. They offer an interesting and novel field of research based on the excellent experimental conditions in the trapped condensates.

In this section we have summarized some of the early experiments which gave confidence that the observed systems were indeed genuine BEC phenomena. They offer spectacular, unique signatures of condensation, they agree excellently with theory, and they suggest many applications in various areas of physics; see next section.

7. Present and Further Prospects

At the present time, more than 20 groups have produced BEC in trapped alkali atoms, and much progress is being reported. Many features of the systems have been investigated: coherent out-coupling of condensates, manipulation of the condensate by the Feshbach mechanism, and utilization of optical lattices to simulate solid state effects. Atom laser beams have been coherently amplified by the MIT group [16] and Kozuma et al. [17]. The atomic analogue of nonlinear optics was observed by Phillips' group at NIST when they achieved four-way mixing of the coherent wave function in the condensate [18].

A recent achievement is the creation of a BEC based on metastable He atoms. These are long lived, they do not form molecules, and they thus offer exciting possibilities as the material for future experimental investigations. The results have been obtained by two groups in Paris, one at Orsay with C. I. Westbrook and A. Aspect as the senior investigators [19] and the other at the Laboratoire Kastler Brossel, ENS, headed by C. Cohen-Tannoudji and M. Léduc [20].

We have already noted that the appearance of vortices is an interesting aspect of the coherence of a condensate. This field of research has progressed greatly and both the Boulder group with Cornell and Wieman and the MIT group with Ketterle have produced spectacular results of vortex formation. The latter group has observed over one hundred vortex lines in the sample. Also other groups have produced vortices, e.g. the Paris group of J. Dalibard.

Utilizing the methods of laser cooling, D. Jin at JILA [21], and also other groups have cooled fermionic gases to a temperature where their quantum correlations become essential. Atomic systems are very favorable for such investigations because, depending on the nuclear spin state, the same species can display either bosonic or fermionic characteristics. Fermionic systems do not undergo BEC, but it is still of great physical interest to investigate the low-energy manifestations of such particles. According to the Pauli principle they pile up into energy states up to a maximum, the Fermi energy. The resulting freezing-out of possible quantum processes restricts the response of the system to atoms at maximum energy. This also explains why evaporative cooling becomes inefficient for fermionic gases, and special methods are needed. An intriguing possibility is to achieve the onset of an ordered phase based on particle pairing in analogy with superconductivity in metals.

The JILA group has showed that utilizing Feshbach resonances, the sign of the particle-particle interaction can be switched suddenly, leading to supernova-like expansion of the condensate [22]. Because fermionic atoms cannot go to the lowest energy state even at zero temperature, they will exert a pressure, which has been observed by Hulet's group at Rice University [23]. This is a laboratory analogue of the internal pressure in a white dwarf star.

The coherent wave function of a condensed atomic system offers a unique novel medium for physical experiments. Its correlated behavior can be utilized to enhance quantum effects up to macroscopic scales. Thus new phenomena can be investigated, which do not directly derive from the condensate but are enhanced by their occurrence in this unique medium. Such applications are to be expected in many areas of research, when the utilization of atomic BEC becomes a standard tool in experimental laboratories. Already there are suggestions to improve the accuracy of high precision measurements and applications in quantum information processing. Technical applications such as bosonic enhancement of lithography have been suggested.

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