The Fuss About Bose–Einstein Condensation

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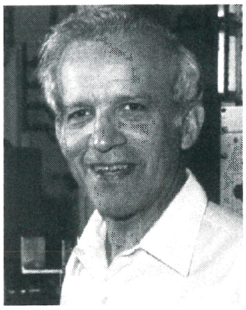
Why all the fuss about Bose–Einstein condensation? chided a friend shortly after the news from JILA in Boulder, Colorado hit the headlines last summer. "Do you atomic physicists really think that Bose condensation is something new?" Others asked me more or less the same question, phrased more or less discreetly. I could see what bothered them. Some headlines suggested that a scientific revolution was upon us, and others implied that Einstein's reputation had been narrowly saved or that a new technology was so close that it was time for venture capitalists to mobilize. "Superatom Discovered!" "Einstein Vindicated!" "Atom Laser!" I argued that newspapers now and then dramatize the news and that one should not confuse a fuss in the press with a fuss in the physics laboratory. The former is likely to be ephemeral but the latter—being made of more substantial stuff—should last awhile.

As for the fuss in the press, the news that Eric Cornell and Carl Wieman at JILA (formerly called the Joint Institute for Laboratory Astrophysics) had observed Bose–Einstein condensation in a vapor of rubidium atoms made the front pages around the world, attracting about the same initial coverage as the discovery of high-temperature superconductivity, the large-scale structures in the universe or the neutrinos from supernova 1987a. Unlike those finds, however, BEC (as it was instantly dubbed) was not really a discovery: it had been predicted and observed decades ago. Nevertheless, the event contained all the essentials of a really good science story.

The report might have made the news merely because its headline contained the magical name Einstein. If the title had been "Scientists See Degenerate Atoms!" the story would not have gotten front page coverage anywhere except possibly the *National Enquirer*. Furthermore, the story involved some everyday ideas—for instance, hot and cold. An account of the coldest atoms in the universe and temperatures below a millionth of a degree is almost enough to make one shiver ("Coldest Atoms in the Universe" was how milk cartons in Sweden carried the news). The experiment itself, invariably described as "tabletop," sounds homey, as if it had been done with rolling pins and muffin pans. And although the actual phenomenon of BEC makes little sense without some knowledge of quantum mechanics, it can nevertheless be portrayed in familiar terms (*Science* pictured the BEC gas as a troop of soldiers marching in lockstep, not a bad analogy). Finally, the story broke at one of those happy times when relatively few horrible things are happening in the world. Science news is generally good news, but according to Gresham's law for the press, good news is forced out by bad news. Fortunately, there was no bad news that day.



As for the real fuss about BEC—the scientific fuss—some atomic physicists were so awed that they likened the search for BEC to the quest for the Holy Grail. The early history of BEC, however, was much humbler than this suggests.

In 1924, Satyendranath Bose, a young Bengali physicist, sent Einstein a paper in which he derived the Planck law by treating photons as a gas of identical particles whose number is not conserved. Einstein saw to the paper's publication and then generalized the problem to an ideal gas of identical particles. In a second paper that followed early in 1925, Einstein, working alone, pointed out that, as the temperature is lowered or the number of particles is increased, a point would be reached where the particles would start to condense into the ground state, essentially coming to rest. Apparently, Einstein thought little of his prediction. "It is pretty, but is it correct?" he wrote to Paul Ehrenfest, and turned his back on the problem forever.

During its first ten years, BEC was a scientific ugly duckling. In 1927, George Uhlenbeck argued in his doctoral thesis that statistical mechanics could not predict a discontinuous phase transition and that BEC was a mere artifact. According to Laszlo Tisza, now an emeritus professor at MIT but in the period 1935–37 a postdoc with Lev Davidovich Landau in Moscow, BEC was never mentioned at Landau's institute.

Nobody took BEC seriously until January, 1938, when superfluidity was discovered. Then, Fritz London took BEC seriously. Tisza, who went to Paris in late 1937 and worked with him, was on hand for these events. (It was during that period that Tisza created the two-fluid model of liquid helium.) London argued that if liquid helium were an ideal gas, Bose condensation would occur at a temperature of 3.2 K, impressively close to the λ transition at 2.2 K, where helium becomes a superfluid.

To apply the theory for an ideal gas to a liquid might seem cavalier. London's arguments, however, were physically motivated, for, in some ways, liquid helium behaves more like a gas than a liquid. Because of its large zero point motion, the atoms shake so much that the liquid almost flies apart. Its density is only about half of what one would guess from the interatomic potential curves. As the temperature of the liquid is increased, its viscosity increases, as for a gas, rather than decreases, as one expects for a liquid. Finally, London argued that superfluidity must be an inherently quantum phenomenon and that, in the quantum regime, helium atoms should obey Bose statistics.

London's conjecture turned out to be only partially correct. Neutron scattering experiments have revealed that superfluid helium has a Bose condensate component essentially at rest. The liquid never becomes totally condensed, because of the atom–atom interactions. At very low temperatures the condensate is only about 10% of the total liquid. A microscopic picture of the

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superfluid has yet to be developed.

Bose condensation has been manifested in other systems, notably in excitons in copper oxide. Cooper pairs in a superconductor are believed to behave like a Bose condensate, and nuclear matter often displays bosonic features. However, until the experiments with cold atoms, a Bose condensate had never been observed in its pristine glory.

The JILA experiment last year created a great stir because the results were so dramatic. Often, the first evidence of a breakthrough is tentative: Experimenters discern a clue almost hidden in the data, tweak the experiment until they are convinced that the effect is real, and eventually become confident enough to convince their friends and, more importantly, the referees. In contrast, BEC in the atomic gas appeared like Venus rising from the sea, fully formed.

The rubidium atoms, confined in a magnetic trap, were cooled to the submicrokelvin regime by laser methods and then by evaporation. The trap was suddenly turned off, allowing the atoms to fly away freely. By taking pictures of the cloud after various time delays, a two-dimensional momentum distribution of the atoms was constructed. As the temperature was lowered, the familiar Gaussian hump of the Maxwell–Boltzmann distribution for a classical gas was pierced by a rapidly rising sharp peak caused by atoms in the ground state of the trap—that is, by the Bose condensate. The first results were good enough for a textbook.

Any doubt that the sharp peak was due to a Bose condensate was dispelled by its shape; the cross section was not circular but elliptical. The mean momentum was almost twice as large along one axis as the other. For a classical gas the momentum distribution is always isotropic unless the gas is flowing. The anisotropy arose because the trap itself was shaped somewhat like a disk. The maximum momentum was along its short axis, a perfect illustration of the Heisenberg relation $\Delta x\ \Delta p \geq h/2\pi$.

Finally, the number of atoms in the peak grew dramatically as the temperature was lowered, as one expects for the onset of BEC. In short, one glance at the data was enough to convince the hardest skeptic.

A few months after BEC was observed at JILA, Wolfgang Ketterle at MIT obtained a Bose condensate in sodium, using a somewhat different trap strategy. Recently, he made a condensate with more than five million atoms, produced at a rate of 200 000 atoms per second. (The first demonstration of BEC involved 2000 atoms, produced at the rate of six per second.) He also developed a method for photographing the atoms while they are confined in the trap. Both the JILA and MIT groups have observed collective oscillations of a Bose condensate, providing the first clear test of the dynamical theory for a weakly interacting many-body Bose system. (See the news story on page 18.)

The experimental realization of BEC was made possible by contributions from a small community of remarkable physicists who developed techniques for cooling, trapping and manipulating atoms. In recent years, several groups started pursuing BEC seriously, and they moved into high gear when the density of trapped atoms became so high that evaporative cooling became possible. Excitement about BEC is high, however, not just because of the novelty and experimental challenge, but because the weakly interacting Bose gas (which is what the atomic cloud becomes) holds many mysteries.

Since the concept of BEC goes all the way back to 1925 and the theory of the weakly interacting Bose gas was developed in great detail by C. N. Yang, T. D. Lee and Kerson Huang 40 years ago, it may not be obvious why BEC should be of much further scientific interest today. Experiments, however, make all the difference. As the possibility of actually seeing BEC drew near, questions started to mount—questions that are by no means trivial. One nontrivial question that gave some experimenters sleepless nights is the time required for the condensate to form. Theoretical predictions ranged from microseconds to essentially the age of the universe. Fortunately, the condensation time turned out to be short, but exactly what it is, and how the atoms condense, remain to be understood.

In the world of phase transitions, BEC is unique because it is the only purely quantum mechanical phase transition—that is, the only phase transition that would still occur without any interaction between the particles. For the first time, essentially every feature of the weakly interacting Bose gas can be studied experimentally. The collective motions in a Bose condensate have barely been probed: Large amplitude motion, for instance, has yet to be studied. The superfluid properties of the gas are by no means well understood. The damping time of the superfluid motion is not known. The transport properties of the condensate have yet to be determined, and its interactions with light and collisional properties remain something of a mystery. All of these questions can now be studied in exquisite detail in systems that can be precisely controlled and manipulated.

Finally, there is the tantalizing possibility of producing coherent beams of atoms from the Bose condensate, creating an "atom laser." Although comparisons of this device with a photon laser are inevitable, at the moment the applications of an atom laser would seem to be limited: Photons can pass through windows and air but atoms cannot. Nevertheless, an atom laser could do for an atom interferometer what a conventional laser does for an optical interferometer: increase its capability perhaps a millionfold.

The underlying excitement about BEC, however, is that this system holds the possibility of a really interesting surprise. Everyone working on BEC knows that superconductivity and superfluidity were not predicted. They were discovered.

By way of a conflict-of-interest statement, I should explain that my enthusiasm for this research is partly because the principal players are former students and close friends. Also, with my colleague Tom Greytak, I have been searching for BEC in hydrogen since time immemorial, or at least since the time before laser cooling had been invented. Hydrogen is attractive theoretically, as always—every atomic property that is important for BEC can be calculated reliably. Experimentally, however, it is fractious if not downright unpleasant. Hydrogen actually forms the most weakly interacting gas, which might appear to be an advantage when the goal is to test the theory of a weakly interacting Bose condensate. Unfortunately, evaporative cooling works much, much better when the interactions are large. To add to the grief, the lifetime of the atomic gas is limited by a decay mechanism (dipole relaxation) that is unimportant in the alkalis. For some time, we have been close to BEC but have lacked a way to see the gas. Recently, we overcame this problem and so we yet expect to see BEC in hydrogen. When we do, we shall look for a unique signature: The heavens will open, the Earth will be bathed in golden light and celestial music will be heard everywhere. Now that is what I would regard as a *real* fuss about BEC.

I am indebted to Thomas J. Greytak, Wolfgang Ketterle, David E. Pritchard, Laszlo Tisza and Carl Wieman for helpful discussions. The early history of BEC is described in Subtle is the Lord, *by Abraham Pais (Oxford U. P., 1988).* ■