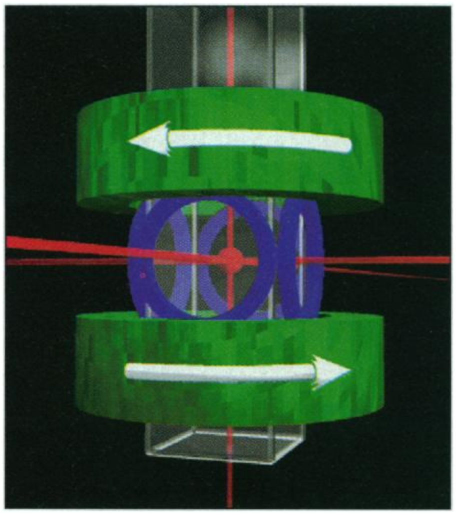
An Intimate Gathering of Bosons

Keith Burnett

All too frequently we hear the term "Holy Grail" breathlessly invoked to describe one goal or another in science. Objections may be raised in almost all cases, on religious grounds if nothing else. I can, however, hold back my objections to using this term for the recent experimental achievements at JILA of the National Institute of Standards and Technology (NIST) and the University of Colorado in Boulder, Colorado. As reported by Anderson *et al.* in this issue (*1*), atomic physicists at JILA have been able, using the techniques of laser and evaporative cooling, to put thousands of atoms into the same quantum state. In short, they have observed the phenomenon called Bose-Einstein condensation (BEC) in a gas of atoms for the first time. The term Holy Grail seems quite appropriate given the singular importance of this discovery.

The idea of BEC has been around for 70 years. It is a phenomenon that arises from the quantum behavior of assemblies of identical particles (*2*). There are perhaps two aspects of the quantum nature of matter that most readily come to mind. The first is the way the wave nature of matter gives us quantization, that is, the characteristic energies of quantum systems. This is, after all, the origin of the word quantum. The second and equally critical aspect comes up when we consider assemblies of identical particles, electrons in an atom being an example. Electrons belong to the family of Fermi-Dirac particles (fermions for short) and obey the Pauli exclusion principle. This means that only one electron can occupy each quantum state of the atom. This fact explains the periodic table of the elements and the stability of matter. In crude terms, we can think of the electrons not wanting their waves (the de Broglie waves representing the probability of a particle's whereabouts) to overlap. The way fermions effectively repel each other and so prevent more than one from being in any quantum state can even be thought of as a kind of purely quantal pressure—the Fermi pressure—that exists even when there are no ordinary forces present.

There is another family of particles, the bosons (short for Bose-Einstein particles) where the reverse phenomenon occurs: We can put as many of them as we wish in the same state. Bose and Einstein elucidated the nature of this family of particles and it now bears their names (*3*). Einstein even showed how the quantum nature of Bose particles can force them into the same state without there being interactions present. This is the phenomenon of BEC referred to above, and its presence has been inferred, rather than directly observed, in a great range of phenomena. These include superfluidity, the property of liquid helium to flow through channels without resistance when it is cooled below a critical temperature called the lambda point (*4*). Condensation is also believed to have been important in the early universe where the Higgs bosons underwent BEC and gave rise to the masses of particles we now observe (*5*). There are, in fact, a whole host of phenomena that rely on the concept of a condensate for their explanation. Good evidence for there being condensed atoms is also available, at least for the case of liquid helium [see the lecture by P. Sokol in (*2*)].



Trapped. Laser trap used by Anderson *et al.* (*1*) to create a BEC. Laser beams (red) enter the glass chamber containing rubidium vapor. Together with magnetic fields produced by coils (blue and green), the optical field traps the atoms, which are cooled as some of the rubidium is allowed to evaporate. Below 170 nanokelvins, the atoms all drop into the lowest energy level, creating a macroscopic condensate of particles all in the same quantum state. [Computer image from (*1*), created by S. Wieman]

So why has is it been so hard to see BEC directly? The first issue is the species we have to start with. Unlike the fermion case, for which we have stable elementary particles, such as the electron, the stable bosons we can easily obtain are composite. An example of this is the ordinary hydrogen atom which is made of two fermions, a proton and an electron, stuck together. There are other composite bosons: ^{4}He and most of the alkali atoms whose properties we can conveniently examine.

To see the effects that Einstein predicted, we need to make the de Broglie waves of the atoms overlap. This would not be a problem if it was not for the fact that atoms, apart from helium and spin-polarized hydrogen (hydrogen atoms with all their spins pointing in the same direction), stick together and form molecules long before the Bose effects become apparent. Even if the atoms do not stick together they still interact strongly and obscure the purely quantal effects that arise from the fact that the particles are identical. Therefore, to avoid the effects of strong interactions, we have to keep the atoms as far apart as possible. So what we want is a gas where the particles are very far apart compared with the range of chemical forces but their de Broglie waves still overlap. The size of the de Broglie wave of an atom gets larger as we decrease the energy, so in principle all we have to do is cool a dilute gas of atoms to a low enough temperature. When the de Broglie waves get big enough to overlap, all the atoms will start to go into the same state, generally the lowest energy state of the box we hold them in. Once this starts to happen, the rise of the number of particles in the ground state rises very rapidly. This is fine in principle, but the problem lies in getting sufficiently low temperatures, lower in fact than anyone had reached until the JILA experiments (*1*).

The effort to observe Bose condensation in systems where the quantum nature of the transition is not obscured by the complications of strong interactions has been long and hard (*2*). It has involved heroic efforts by people in several communities. I will focus on the developments in my own field—atomic physics. There have also been reports of the observation of BEC in an excitonic gas (*6*). The first experiments on atoms used spin-polarized hydrogen (*7*). This is a remarkable substance as it is the only one that remains a gas even at absolute zero. A great deal of important physics has been learned to date in a variety of experiments based on spin-polarized hydrogen (*2*). These experiments result from the ability to trap spin-polarized hydrogen in a magnetic field and have come very close to the observation of BEC in recent years (*8*). The gas is cooled in the final stage of the experiment by using a technique called evaporative cooling. In this method the hotter atoms held in the trap are removed, with the ones left behind being cooler and

The author is in the Department of Physics, Clarendon Laboratory, Oxford University, Oxford OX1 3PU, UK.

denser on average. This technique was also used in the second stage of the JILA experiments where laser cooling of gas was the first step. The most recent experiments are performed with rubidium-87 atoms, because it is possible to cool them to very low temperatures and make their de Broglie waves correspondingly large. This means that one should be able to observe BEC in a very dilute gas. The more dilute the gas the less likely the atoms are to stick together and be lost from the trap. Its properties are also easier to predict, and the BEC process is closer to an ideal case, that is, unpolluted by the effects of interactions.

The experiment at JILA used a combination of laser cooling and evaporation (*1*). Laser cooling the alkali atoms can be used to produce a gas at temperatures around 1 μK and densities of 10^{12} particles per cubic centimeter. The use of alkali atoms is critical as it is their ground-state structure that enables one to cool them to this low initial temperature. At this point the lasers have to be turned off as they cannot produce a colder, denser gas without the interaction between the particles in the presence of the laser causing heating. The atoms are then transferred to a magnetic trap that can be used to push toward BEC by using evaporative cooling. The end point is an assembly of atoms all in the same quantum state in the bottom of the trap.

Several other groups are close behind in the race (see the News story on p. 152) and will surely reach the finish line soon. This is really only the beginning for the field and should, I believe, be looked upon in the same way as the development of the laser. We have the prospect of manipulating and examining the behavior of assemblies of atoms all with the same wave function—very much like the photons (which are bosons too) released by stimulated radiative emission in a laser. The quantum nature of their wave functions is then brought up to the macroscopic—or more accurately, mesoscopic—domain. This will make it possible to explore a wide range of phenomena in macroscopic quantum systems. The condensates will also be a new laboratory for quantum statistical phenomena that are inaccessible to other conventional techniques. It should be possible, according to recent predictions, to tune the strength and sign of the weak interactions between the atoms. In principle, one can now study in real time phenomena that have been addressed only by theory: spontaneous symmetry breaking and decay of unstable macroscopic states. The technology, because of its essential simplicity, also has the possibility of being extended enormously to different atoms and other configurations. This will include the possibility of making extremely bright sources of atoms, a veritable atom laser, that is bound to have many applications in pure science and technology.

References and Notes

1. M. H. Anderson *et al.*, *Science* **269**, 198 (1995).
2. A. Griffin, D. W. Snoke, S. Stringari, Eds., *Bose-Einstein Condensation* (Cambridge University Press, Cambridge, 1995). This is an excellent set of review lectures on most aspects of BEC.
3. S. N. Bose, *Z. Phys.* **26**, 178 (1924); A. Einstein, *Sitzungber. K. Preuss. Akad. Wiss.* **1924**, 261 (1924); *ibid.* **1925**, 3 (1925).
4. P. Nozieres and D. Pines, *Theory of Quantum Liquids Vol 2: Superfluid Bose Liquids* (Addison Wesley, Redwood City, CA, 1990).
5. A. Vilenkin and E. P. S. Shellard, *Cosmic Strings and Other Topological Defects* (Cambridge University Press, Cambridge, 1994). This book has a very thorough account of phase transitions in the early universe.
6. J. L. Lin and J. P. Wolfe, *Phys. Rev. Lett.* **71**, 1222 (1993).
7. I. F. Silvera and J. T. M. Walraven, *ibid.* **44**, 164 (1980).
8. J. M. Doyle *et al.*, *ibid.* **67**, 603 (1991).

Methyl Chloroform and the Atmosphere

A. R. Ravishankara and D. L. Albritton

The atmospheric abundance of methyl chloroform, CH_3CCl_3, a compound of only anthropogenic origin, is actually decreasing because of emission reductions in compliance with the United Nations Montreal Protocol and its subsequent amendments. This observation, reported by Prinn and co-workers elsewhere in this issue (*1*), is based on data from surface-level monitoring stations. The observed trends in methyl chloroform abundance have a few straightforward scientific consequences and substantial policy relevance.

Methyl chloroform is the first substance regulated under the Montreal Protocol that has shown a distinct decrease in atmospheric abundance, not just a decrease in its rate of growth. The abundances of long-lived chlorofluorocarbons (CFCs) have also been affected under the Montreal Protocol. Not only have their growth rates slowed but they are now close to zero (see figure). In the next few decades, the abundance of these long-lived CFCs will also start decreasing. The first message from these findings is clear: Compliance with the Montreal Protocol will decrease the amount of chlorine-containing species in the atmosphere. Because the majority of the chlorine reaching the stratosphere is derived from anthropogenic releases into the atmosphere, the concentration of chlorine in the stratosphere will decrease. Further, because the evidence is conclusive that chlorine, with contributions from bromine-containing compounds, is responsible for the Antarctic ozone "hole" and because the weight of the evidence links anthropogenic chlorine and bromine to the well-documented global ozone depletion, the decrease in atmospheric chlorine levels should lead to a slow recovery in stratospheric ozone levels, if everything else (such as temperature, aerosol levels, and so forth) remains approximately the same.

The abundance of methyl chloroform has already decreased because its atmospheric lifetime is comparable with the time scale over which it has been regulated; hence, the atmospheric response to reduced emissions is relatively prompt. Shorter lived chlorine compounds will decrease in abundance more quickly; hence, the earliest contribution to the recovery of the stratospheric ozone layer will come from the shortest lived compounds. Methyl chloroform is the forerunner in this category. Therefore, the second message associated with the methyl chloroform observations is simply that the atmosphere responds more quickly to reductions in emissions of shorter lived compounds.

This simple and obvious, yet profound, point has several implications. For example, if future work were to suggest that any of these new chemical species have unexpected deleterious effects on the atmosphere, then their emission could be curtailed and atmospheric recovery would be rapid. Furthermore, for equal emissions, a shorter lived species would not build up to as high an abundance as a longer lived molecule would. [For example, even though the emissions of methyl chloroform (600 to 700 kilotons per year) were almost double those of CFC-12 (~400 kilotons per year) during the 1980s, its atmospheric abundance was one-fourth that of CFC-12; see figure.] The above implications are true for all chemicals released into the atmosphere. Therefore, if a more rapid recovery were deemed desirable, a shorter lived chemical would be more effective in

The authors are at the National Oceanic and Atmospheric Administration (NOAA), Aeronomy Laboratory, 325 Broadway, Boulder CO 80303, USA.