Physics Today

Gaseous Bose–Einstein Condensate Finally Observed

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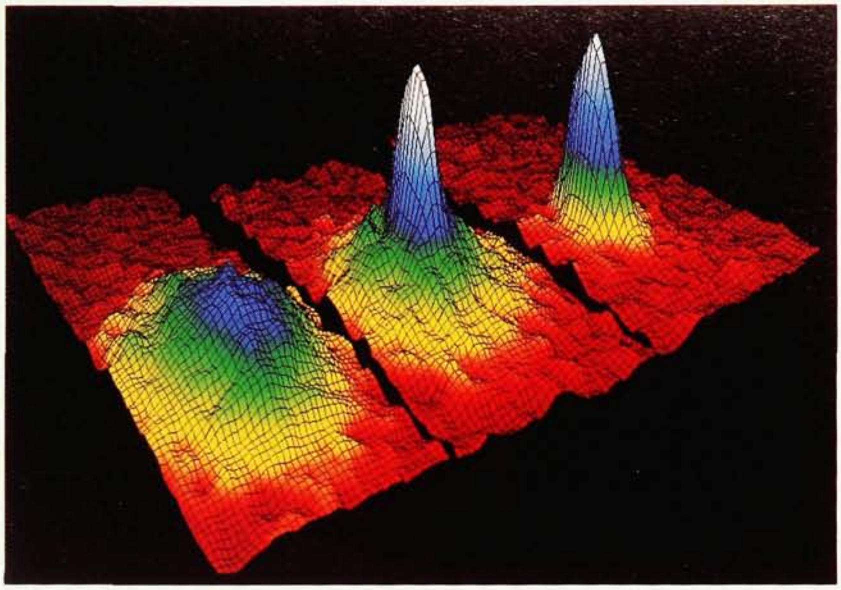
Citation: Physics Today **48**(8), 17 (1995); doi: 10.1063/1.2808119
View online: http://dx.doi.org/10.1063/1.2808119
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/48/8?ver=pdfcov
Published by the AIP Publishing

Gaseous Bose–Einstein Condensate Finally Observed

Researchers using a clever new magnetic trap have cooled a cloud of rubidium-87 atoms to a record-low 20 nanokelvins and achieved the Holy Grail of low-temperature atomic physics: Bose–Einstein condensation in a gas.



BOSE CONDENSATION CAN BE SEEN in these velocity distributions of atoms in an evaporatively cooling cloud of ^{87}Rb atoms. Before condensation begins (left), the distribution is isotropic, as expected for a gas in thermal equilibrium. The condensate appears (middle) as a fraction of atoms that have velocities close to zero. The distribution is elliptical, as expected if all the condensed atoms are in the ground state of the elliptical potential. Continued evaporation leads to an almost pure condensate of about 2000 atoms (right). Each image is $200 \times 500\ \mu$m and is derived from the shadow of the atom cloud after 60 ms of free expansion. (Courtesy of Michael Matthews, JILA.)

About seven decades ago Satyendra Nath Bose and Albert Einstein predicted that a gas of noninteracting integer-spin particles would condense into a macroscopic quantum state when cooled below a critical temperature. Of course Bose–Einstein condensation (BEC) has long since been seen in superfluid ^{4}He and superconductors, but the condensing systems in these examples are far from being noninteracting gases; relatively strong interactions between the condensing particles greatly complicate the theoretical analysis and the experimental behavior. For more than 15 years groups have been cooling and compressing clouds of atoms on a quest to produce and observe a Bose–Einstein condensate in a near-ideal gas. They pushed their devices to the limit, seeking to traverse 15 orders of magnitude of phase-space density, and as each technique proved insufficient they developed ingenious variations to create ever colder and denser states.

The Holy Grail of this quest has now been found and displayed in convincing fashion by a group in Boulder, Colorado. Eric Cornell (NIST), Carl Wieman (Joint Institute for Laboratory Astrophysics), Michael Anderson (University of Colorado) and coworkers produced the long-sought BEC in a cloud of rubidium-87 atoms, which they cooled with a sequence of magneto-optic and evaporative magnetic cooling schemes.[1] The condensate formed at temperatures of about 170 nanokelvins, and in the most completely condensed samples about 2000 atoms were in a single quantum state. The group can maintain these conditions for longer than 15 seconds.

The results are a vindication for Wieman, who initiated the Colorado BEC research program and vigorously promoted the idea of seeking BEC in trapped alkali atoms. His group has worked intensively toward BEC for six years, but he is quick to credit Cornell with the development that got them past the final hurdle: a new type of magnetic trap—a time-averaged orbiting potential, or TOP, trap. Cornell in turn credits postdoc Anderson with putting the concept into action in the lab. "For instance," Cornell told us, "our first TOP trap was pretty crude, and Mike realized that we had to build a second one with closely matched coils and smoother driving waveforms." Other coworkers include Jason Ensher, Michael Matthews, Nathan Newbury, Christopher Myatt, Richard Ghrist and theorists John Cooper and Murray Holland.

Daniel Kleppner (MIT), a pioneer in the field, hailed the work as "spectacular." "Not only did they observe Bose condensation," he told us, "but they did it brilliantly. Often the first data on a new phenomenon is ambiguous and hard to interpret. But these results are so beautiful they could go into a textbook. They have three pieces of evidence, every one of which is clear and convincing by itself."

The Colorado group saw the three signatures of BEC by imaging the velocity distribution of the atoms in the cloud. Above the transition temperature there is a broad, spherically symmetric distribution of velocities, consistent with a cloud in thermal equilibrium. The first signal of the Bose-condensed atoms is the appearance of a narrow peak in the distribution, centered on zero velocity. (See the figure above.) Second, the fraction of such atoms increases abruptly as the temperature falls (see the figure on page 18), indicating the presence of a phase transition. Finally, the peak is anisotropic, as would be expected for atoms all having the ground-state wavefunction of the ellipsoidal potential at the center of the magnetic trap. "It's a very clear signal," affirms Steven Chu (Stanford University).

BEC basics

To achieve Bose–Einstein condensation one must produce a sample of bosonic particles whose de Broglie wavelength λ is larger than the mean spacing between the particles. Then, loosely speaking, the wavefunctions of the atoms overlap sufficiently that individual atoms cannot be distinguished, and Bose statistics favors the condensation of all the atoms into a single quantum state. A more precise computation for an ideal gas predicts that the phase transition occurs when the dimensionless phase-space density $\rho_{ps} = n\lambda^3$ exceeds 2.612 (where n is the number density).[2] If the density of the gas is low (as is required for a real gas to approximate an ideal gas) this condition requires extremely low temperatures. For a gas of particles with mass m at temperature T, the de Broglie wavelength λ equals $h/(2\pi mkT)^{1/2}$.

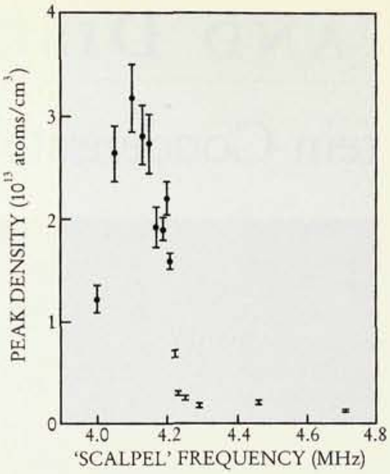
Evidence of BEC in a weakly interacting gas *has* been seen before—in a gas of excitons in a semiconductor.[3] However, that system doesn't satisfy the Grail seekers because the residual interactions are not well understood, the condensate doesn't last very long and it is difficult to extract data about the condensate.

Just as different medieval knights set off on various routes questing after the Grail of mythology, many experimental groups have pursued BEC, each using its own combination of techniques and atomic systems. Two major campaigns have charted out much of the territory.

The first is work using spin-polarized atomic hydrogen, which has the unusual property that it remains a gas all the way to absolute zero. Groups led by Thomas Greytak and Kleppner at MIT and Isaac Silvera and Jook Walraven at the University of Amsterdam began this work more than 15 years ago.[4] (Silvera now has an active program at Harvard.) With hydrogen, cryogenic methods can be used to cool the atoms to very low temperatures before they are loaded into a magnetic trap to take them the rest of the way to the BEC threshold. Greytak tells us this technique should give his group a larger condensate than in the alkali systems—perhaps 10^{11} atoms as compared with 10^4.

Evaporative cooling

About ten years ago Harold Hess, then a postdoc with the MIT team and now at AT&T Bell Labs in Murray Hill, New Jersey, made a seminal contribution to the BEC field when he proposed the technique of evaporative cooling in a magnetic trap: By lowering the potential of the trap, one allows the high-energy tail of the distribution—the hottest fraction of atoms—to escape from the system. The lowering is performed slowly enough to allow the remaining, cooler atoms to rethermalize by elastic collisions.



A SUDDEN INCREASE IN THE DENSITY at the center of the ^{87}Rb sample occurs as the evaporative "rf scalpel" cuts to lower frequencies, producing a smaller, denser, colder cloud of atoms. The abruptness of the increase at about 4.23 MHz is strong evidence of a phase transition. Below about 4.1 MHz the scalpel starts to cut away the condensate itself. (Adapted from ref. 1.)

Then the new high-energy tail escapes, and so on, much in the same way that a cup of coffee cools by evaporation.

In a variant of this technique known as rf-driven evaporative cooling, a radiofrequency signal is tuned so as to excite only those atoms at the outermost edges of the trap, flipping their spins and ejecting them from the trap. The transition energy for such a process varies according to an atom's location because of the trap's inhomogeneous magnetic fields. By slowly ramping down the frequency of the rf signal one can drive the evaporation process without lowering the trap fields, allowing one to produce a denser, more tightly confined sample. Cornell calls this technique the "rf scalpel," because the rf field "slices away" all those atoms energetic enough to stray too far from the trap center.

Most recently, Kleppner told us, John Doyle (Harvard) has taken the evaporative cooling techniques the furthest for the MIT group. Greytak and Kleppner are confident that they can achieve BEC with their system; indeed, they got within a factor of 3 in phase-space density four years ago. The stumbling block is that they have had no way of observing a condensate if it formed. For the past four years their only observation methods have involved first releasing the atoms from the trap. In June, however, they succeeded in detecting the hydrogen atoms *in situ* using optical techniques.

Alkali atoms and leaky traps

The second major campaign uses alkali atoms. Unlike spin-polarized hydrogen, alkali atoms should form a solid at low temperatures, but a metastable gaseous state can be maintained even at nanokelvin temperatures.

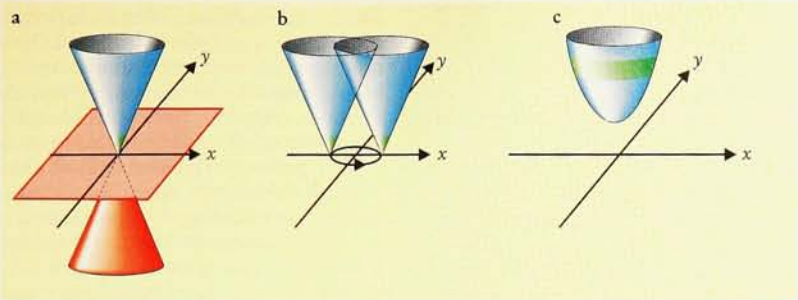
The atoms are initially cooled from room temperature not by cryogenic techniques but by laser cooling[5] in a magneto-optic trap, or MOT.[6] Then, when the densities are too high for efficient laser cooling, one switches to the evaporative cooling methods developed by the hydrogen groups. Wieman told us that when he first advocated this scheme, "many of the theorists said that this approach to BEC was impossible." Undeterred, his group went ahead, studying collisional loss processes and cross sections in trapped alkalis, laying the foundations necessary for this approach. Cornell joined the team about five years ago, initially as a postdoc, and he and Wieman have collaborated closely ever since.

Competing with the Colorado group in recent years has been another MIT group, that of Wolfgang Ketterle, Kendall Davis, Marc-Oliver Mewes, Michael Joffe, Michael Andrews and Klaasjan van Druten. "The Colorado group and my group were in a head-to-head race for the past two years," Ketterle told us. His group cools sodium atoms.

An innovation by Ketterle and David Pritchard (MIT) was the dark MOT. In a conventional MOT, three orthogonal pairs of laser beams (and a seventh "repumping" beam) cool the atoms and compress them into a spot where the beams overlap. But Wieman's group discovered that the intense laser beams prevent further compression of the gas because scattering of photons between the atoms creates an effective repulsion.

Ketterle and Pritchard's trick to overcome this limitation is to use a "hollow" repumping laser beam, produced, for example, by having a small opaque spot on a window that the beam passes through. Once the atoms are in the center of the trap they enter this dark spot, where they remain in their ground state, impervious to the problematic effects of the trapping beams.

The Colorado group uses a dark MOT to reduce the amount of time the trapped atoms are in the excited state. When the excited atoms collide they tend to do so very inelastically and are ejected from the trap. Because the researchers begin with a



THE MAKING OF A TOP TRAP. a: A conventional quadrupole trap has a conical potential (blue) that traps (for example) atoms in the $m = -1$ state. Near the point of the cone (green), such atoms are readily flipped to the $m = 0$ or $+1$ states, which see the red potentials and consequently are lost from the trap. b: Adding a uniform rotating magnetic field has the effect of rotating the quadrupole potential in space. c: The $m = -1$ atoms are now confined by the time-averaged potential, and only hot atoms are lost near the orbiting instantaneous zero point (green).

very low vapor pressure of Rb they must run their MOT for a long time to collect a large number of atoms, so they have to suppress losses from inelastic collisions during that collection period.

But even the use of dark MOTs followed by cooling with optical molasses[5] could only bring the Na or Rb atoms to within about 6 orders of magnitude of the phase-space density needed for BEC. To get further, both groups load their MOT-compressed atoms into a magnetic trap—a quadrupole trap—where evaporative cooling can be carried out. In May 1994 both groups announced the observation of evaporative cooling in an alkali system.

Evaporative cooling with a quadrupole trap brought each group's atoms a factor of 5–10 closer to BEC (and Ketterle's group subsequently pushed this to a factor of 200 or so[7]), but neither group could get much further without solving another problem: a leaky "hole" right at the coldest point of their traps.

Plugging the hole

The field of a conventional quadrupole trap[8] is produced by two coils, one on each side of the trap, with their currents circulating in opposite directions. Atoms with a magnetic moment experience an axially symmetric potential that drops linearly to zero at the central point between the coils. Along any radial direction the potential is conical. (See the figure above.) This potential confines the atoms, with the coldest atoms collecting near the zero-field point.

As an atom moves around in the trap its spin remains aligned with the local field—except very near the zero-field point, where the field direction changes sharply and all spin orientations have nearly the same energy. An atom crossing this region can have its spin flipped, and then instead of sitting at the bottom of a confining potential, it finds itself perched at the highest point of a potential that quickly drives it out of the trap.

Ketterle and his group are using an optical method to plug this hole in their trap. The hole is a tiny region—a few micrometers across—in a cloud of atoms spread over more than 100 μm. The experimenters shine a tightly focused, high-power laser beam across the hole. The beam is far off resonance so it does not heat the sodium cloud via excitation and spontaneous emission. Nevertheless a dipole force repels atoms away from the beam and hence the hole. With the hole plugged, Ketterle's group immediately got a further factor of 1000 closer to BEC, leaving them a tantalizing one order of magnitude away as this article goes to press.

Cornell had *his* idea for plugging the zero-field hole on the flight home from an April 1994 meeting. One might think that adding a uniform field to the quadrupole trap would remove the zero-field hole, but in fact the effect is to shift the potential to a new location that depends on the orientation of the added field. The atoms are attracted to the new zero-field point and "fall out" of the trap there. Cornell's idea was to change the orientation of the added field faster than the atoms could move to the new hole, and to keep changing it. "Then I thought, well, a nice smooth continuous way to do that is to apply a rotating field. And so on the airplane I worked out the integral for the time-averaged potential, and it all looked pretty promising."

His group added the rotating field by driving a sinusoidal current 90° out of phase through two orthogonal pairs of coils. The rotation rate is carefully set between two time scales. It is slow enough that an atom's spin can remain aligned with the instantaneous magnetic field, but it is fast enough that the atom's motion through space is essentially governed by the time average of the potential. The time average is an ellipsoidal harmonic potential. (See the figure at left.)

Because the minimum of the potential is now smooth and nonzero, the spin-flipping problem is greatly reduced: Small clouds remained trapped for 20 times as long as in the quadrupole trap. The TOP trap also has evaporative cooling automatically built into it. The instantaneous zero point of the rotating quadrupole field is on the outskirts of the trapped cloud. As the zero point passes by, atoms at that location still tend to be spin-flipped and lost from the trap—but those atoms tend to be the most energetic in the cloud.

Continued evaporation can be maintained either by ramping down the rotating field, which draws the rotating zero point closer in, or by applying the rf scalpel mentioned earlier. The latter technique gave Cornell a factor-of-1000 improvement in the phase-space density and temperatures as low as 200 nK with ^{87}Rb atoms in the F=1 state.[9]

The Grail and beyond

At conferences in May 1995 Cornell and Anderson reported temperatures as low as 35 nK. The question on everyone's lips before Anderson's talk was, "Have you seen it yet?" Indeed, some tantalizing evidence of BEC had been seen, but nothing conclusive. A couple of weeks later, however, the evidence was firm enough for Cornell to announce the observation of BEC in F=2 ^{87}Rb atoms at the International Conference on Laser Spectroscopy in Capri. The F=2 state, having a greater magnetic moment than F=1, can be compressed more by the trap.

A final trick to seeing BEC was to let the sample equilibrate in the trap for 2 seconds at the end of the cooling process.[1] "We need to investigate this further," Wieman told us. "It might involve some interesting dynamics of the condensate. There are basically two theoretical predictions for the time it takes a condensate to form. One is essentially infinite, and the other is a nanosecond. We always joked that if we could see a condensate we ought to be able to resolve the discrepancy."

The researchers observe the atom clouds by carefully relaxing the trapping fields and allowing the atoms to expand freely for 60 ms. (At this point the atoms are in fact at their lowest temperature—as low as 20 nK.) They then shine a pulse of resonant laser light through the cloud. The shadow of the cloud provides a map of the atom distributions and hence of the velocity distributions before the expansion. (See figure on page 17.)

While the quest for the Grail has now ended, the study of it is just beginning. Those studies will include laser spectroscopy of the condensate, exploring how light interacts with coherent matter, and experiments analogous to the classic experiments on superfluid helium (persistent sloshing, second sound and so on).

The success or failure of competing groups will also yield valuable information. In the first week of July, a group led by Randall Hulet at Rice University, in Houston, Texas, surprised the BEC community by reporting they had cooled clouds of ^{7}Li to within a factor of 3 of the quantum degeneracy point. As we go to press, Hulet tells us they have now pushed well into the degenerate regime. Hulet's team includes Curtis Bradley, Charles Sackett and Jeffrey Tollett.

The group uses a novel harmonic magnetic trap with permanent magnets. Such a trap doesn't suffer from the hole of a quadrupole trap but only allows much lower evaporation rates than either a quadrupole or TOP trap does. Hulet's group gets around this deficiency by achieving evaporation times as long as 7 minutes. Hulet told us that laser light directed through the coldest and densest clouds produced a diffraction pattern consistent with a small compact core. Further study is needed, however, to substantiate these results.

A condensate of ^{7}Li would be more than just another condensate. ^{7}Li has a negative s-wave scattering length (which contributes an additional attraction in collisions) while that of ^{87}Rb is positive (causing a repulsion). Theorists have shown that in the low-density limit the condensate is stable in equilibrium only for the positive (repulsive) case, but whether a condensate might still form in the negative case has been controversial. Studies comparing ^{87}Rb with ^{85}Rb should also shed light on this issue because ^{85}Rb probably has a negative scattering length.

Yet another approach to BEC is that of Chu and Mark Kasevich at Stanford, who in late summer of 1994 achieved evaporative cooling with all-optical traps. These trap atoms in all spin states, including the lowest-energy spin state, unlike the magnetic traps, which trap only a single spin state and are consequently unstable with respect to spin flips.

Chu points out that the condensate is a source of atoms in a single quantum state. "Once you have that you can start to play all sorts of games. You can think of applications equivalent to an atom laser." He also points out that one could form a degenerate Fermi gas, for example by cooling a mixture of fermionic and bosonic lithium isotopes in a trap like Hulet's. (A purely fermionic sample would be much more difficult to cool.)

But perhaps Theodor Hänsch (University of Munich), one of the inventors of laser cooling of atoms, sums up the prospects the best: "It is like a door that has opened to a new world." Researchers everywhere are saddling up to explore that realm.

GRAHAM P. COLLINS

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Los Alamos Accelerator Group Reports Its Evidence for Neutrino Oscillation

A handful of muon neutrinos at the LAMPF accelerator appear to have undergone a metamorphosis. If it's true, it tells us that some neutrinos have mass.

Despite its somewhat hectic provenance, the paper submitted to *Physical Review Letters* in June by the Liquid Scintillator Neutrino Detector collaboration[1] at Los Alamos brings us the first serious evidence of neutrino oscillation in an accelerator experiment. All previous substantial hints of neutrino oscillation have come from astrophysical sources, over which experimenters have no control. (See PHYSICS TODAY, April, page 19.) The LSND result, like all the astrophysical evidence, is still inconclusive. But it has set the particle physics and cosmological communities abuzz.

The standard model of particle theory assumes, for simplicity, that all three neutrino varieties (associated respectively with the electron, the muon and the much heavier tau lepton) are massless. But the theory, and the experimental limits, can accommodate small neutrino masses. If neutrinos can be shown to oscillate from one "flavor" to another, the two varieties must differ in mass; they cannot both be massless.

The demonstration of neutrino oscillation would enrich the standard model, perhaps pointing the way to a more unified particle theory. Cosmologists, for their part, are particularly interested in the range of neutrino masses (on the order of an electron volt) indicated by the new Los Alamos result. It suggests that neutrinos may be significant contributors to the "dark matter" required by the cosmologists' own standard model.

Tons of baby oil

The LSND experiment at Los Alamos, initiated by Hywel White and William Louis, began taking data in 1993. The detector—basically 167 tons of mineral oil spiked with a gallon of scintillator and watched over by more than a thousand photomultiplier tubes—is shown on page 21. It sits 30 meters downstream of a massive beam stop that brings the Los Alamos Meson Physics Facility (LAMPF) accelerator's high-intensity 800-MeV proton beam and its mesonic debris to rest. The lineup of impediments upstream of the detector is designed to produce an abundance of muon antineutrinos ($\bar{\nu}_\mu$) with the least possible contamination of electron antineutrinos ($\bar{\nu}_e$), while keeping everything except neutrinos (and antineutrinos) from reaching the detector.

The task of the phototube array is to look for inverse-beta-decay scattering events inside the detector, that is

$$\bar{\nu}_e + p \rightarrow e^+ + n$$