

At Long Last, a Bose–Einstein Condensate is Formed in Hydrogen

When Thomas Greytak and Daniel Kleppner at MIT started out 22 years ago to form a Bose–Einstein condensate by cooling and compressing a gas of hydrogen atoms, they did not realize just how arduous the journey would be. But their ingenuity and perseverance paid off this past summer when graduate students Dale Fried and Tom Killian awakened them at their homes in the early morning hours of 12 June to report evidence of a Bose condensate in their hydrogen trap.^{1,2}

The MIT researchers were not the first to cross the finish line in the race to form a gaseous Bose–Einstein condensate, a collection of atoms in a single, macroscopic quantum state. Eric Cornell (National Institute of Standards and Technology in Boulder, Colorado), Carl Wieman (Joint Institute for Laboratory Astrophysics), Michael Anderson (University of Colorado at Boulder) and their colleagues took those honors in 1995 by achieving Bose–Einstein condensation (BEC) in a gas of rubidium-87 atoms.³ (See PHYSICS TODAY, August 1995, page 17.)

An MIT group headed by Wolfgang Ketterle followed close on their heels with a condensate of sodium atoms,⁴ and Randall Hulet and his group at Rice University later demonstrated BEC in lithium.⁵ (See PHYSICS TODAY, March 1996, page 18, and August 1996, page 18.) As pioneers in the field, however, Greytak, Kleppner and colleagues were sentimental favorites, and their achievement earned a standing ovation when Kleppner reported it at the Enrico Fermi school in Varenna, Italy, this past July.

The race has been a friendly rivalry, and the various groups have helped one another along the way. In their quest, Greytak, Kleppner and colleagues developed a technique of evaporative cooling, which was adopted by the groups working with alkali atoms. Those groups in turn developed a method of RF-driven evaporative cooling, which proved crucial to MIT's hydrogen group.

As they reported at the International Conference on Atomic Physics held in Windsor, Ontario in August, Greytak, Kleppner and their colleagues estimate that the hydrogen atoms in their trap condensed at a temperature of 50 microkelvin, with a

▶ Because hydrogen atoms interact quite weakly, they are at the same time desirable and difficult candidates for the low temperature collapse into a common quantum ground state predicted in the 1920s.

density of a few times 10^{15} atoms/cm³. Although the proportion of hydrogen atoms in the condensate was only a few percent, the total number of atoms in the condensate was more than 10^8 , at least ten times as many atoms as the maximum so far achieved in alkali condensates.

The interest in hydrogen

Hydrogen atoms of opposite spin attract one another, combining to form molecular hydrogen when a third body is present. But a gas of spin-polarized hydrogen atoms is the best approximation we have to the ideal gas of non-interacting, identical particles that Satyendra Nath Bose and Albert Einstein had in mind in the 1920s when they predicted a collapse below a certain temperature into a common ground state, with the atoms essentially at rest. Although these aligned hydrogen atoms do interact, they do so weakly, and the properties of a hydrogen Bose–Einstein condensate can be readily calculated from first principles to facilitate any comparison with experiment.

A stable collection of spin-polarized hydrogen atoms was demonstrated in 1980 by Isaac Silvera and Jook Walraven, who were both at the University of Amsterdam at the time. (See PHYSICS TODAY, June 1980, page 18.) They placed the atoms in a strong magnetic field that attracted those atoms with electron spins down and repelled those with spins up. When the electron spins are polarized, the nuclear spins are induced to line up as well, so that one automatically gets a doubly polarized gas, as Greytak, Kleppner and Richard W. Cline demonstrated in 1981. Silvera, now at Harvard University, confesses that, back in the 1980s, he thought BEC was only a few years away. He is still in the game, and now thinks it'll be only a few months before he, too, achieves hydrogen BEC.

Evaporative cooling

For a Bose–Einstein condensate to

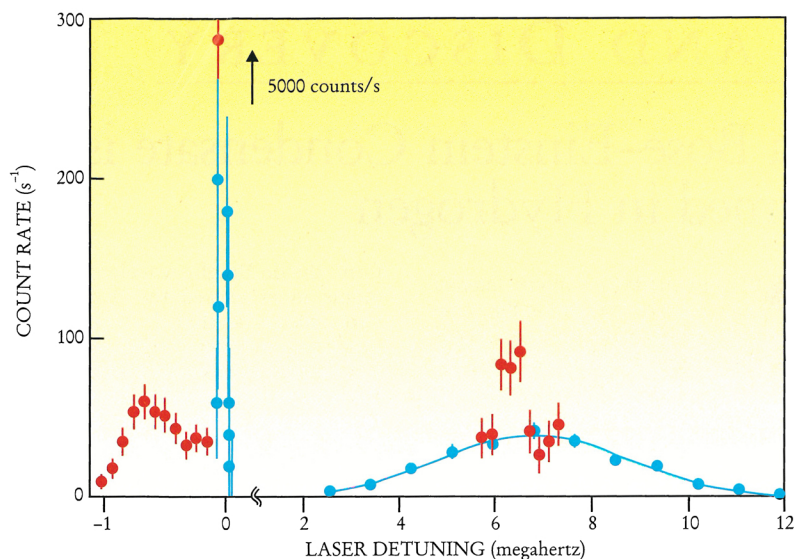
form, the de Broglie wavelength of the atoms must exceed the distance between atoms, so that the atomic wavefunctions overlap. The de Broglie wavelength is inversely proportional to the square root of both the mass and temperature. Thus, for BEC, one needs both a low temperature and a high density. For a given temperature, hydrogen, as the lightest atom, should have the longest wavelength, making BEC achievable in principle at a higher temperature than for other atoms.

Nevertheless, we are still talking about temperatures significantly below 40 millikelvin—the lowest one can reach by applying standard cryogenic techniques to spin-polarized hydrogen. To get the atoms colder than that required two more steps: evaporative cooling and RF-driven ejection.

Evaporative cooling is a technique developed in the 1970s by researchers working on atom traps. Its application to spin-polarized hydrogen relies on a critical suggestion made in 1986 by an MIT postdoc, Harald Hess (now at Phase Metrics in San Diego).⁶ Until then, MIT's hydrogen team had been working with atoms whose spins were antiparallel to the magnetic field direction; such spin-down atoms were attracted to a high field region. Because it is not possible to have a local maximum of the magnetic field in a source-free region, the atoms could not be confined by the field alone but required material walls as well. Hess was looking for a solution to the loss of hydrogen atoms by collisions with the walls of this bottle. Why not eliminate the need for walls altogether, he thought, by trapping spin-up atoms in a magnetic field that has a local minimum in the center of the trap?

This plan opened the door for evaporative cooling, in which the hottest atoms are essentially skimmed off, so that those remaining come to equilibrium at a lower temperature. Such evaporation is accomplished by gradually lowering the field strength.

The trap that Greytak and Kleppner's group uses for evaporative cooling is very long and thin, with an aspect ratio of 400:1. Magnets along the side produce a cylindrical quadrupole field that confines atoms radially, and two solenoids at either end trap them axially. For evaporative cooling,



BOSE-EINSTEIN CONDENSATION is seen in the two-photon spectrum of trapped hydrogen, a composite made from scans focusing on both the thermal gas (blue circles) and the condensate (red circles). Depending on whether the thermal atoms absorb counter- or copropagating photons, their spectrum is an intense, narrow peak near the origin or a recoil-shifted and Doppler-broadened feature to the right (near 7 MHz). Atoms in the condensate give rise to a recoil-shifted peak (near 6–7 MHz) that is narrower than in the thermal gas because of the small momentum spread, and a nonrecoil line that is shifted to the left of the origin by the high density of the condensate. The frequency scale changes near the origin. The laser detuning is relative to the 243 nm 1S–2S excitation. Only 10 percent of the thermal gas is seen because it is larger than the laser beam. (Adapted from ref. 2.)

the researchers reduce the field of the solenoid at one end, removing the most energetic atoms that are able to reach that part of the trap. In 1991, with a second generation of this device, then-graduate student John Doyle (now an associate professor at Harvard) took the MIT group as close as it had been to the required conditions for BEC—100 microkelvin and 8×10^{13} atoms/cm³, just a factor of three above the critical temperature at that density.⁷

But cooling by evaporation becomes increasingly inefficient at these low temperatures. Its effectiveness is limited by the very property that makes hydrogen attractive for BEC: the weakness of its interactions. Thus the MIT researchers working on hydrogen BEC turned toward the RF-driven ejection technique that had recently been developed to cool alkali atoms, modifying their trap to accommodate it. In this technique, one applies an RF pulse to flip the spins of atoms on a surface of constant magnetic field: By proper choice of RF frequency, one targets the magnetic field surface where the most-energetic atoms reside. Once its spin is reversed, an atom feels a force away from rather than toward the center of the trap. This method is more efficient than removing atoms just at one point of the cloud, as in the original ejection technique. The trick took the MIT

team the one last step toward BEC.

Detecting the condensate

But how were Greytak, Kleppner and coworkers to know when they had a condensate? The groups that have formed BEC in alkali atoms have shown beautiful color pictures of condensates, with sharp spikes indicating the high densities in the centers of their traps. But hydrogen atoms reveal themselves through much shorter wavelengths of radiation (Lyman alpha lines) that do not yet lend themselves to visual imaging techniques.

In their earliest work, the MIT researchers had to release the gas from the trap to determine its density distribution. Currently, though, they use two-photon spectroscopy to determine the density distribution *in situ*. Greytak told us that their setup, which is patterned after one developed by Theodor Hänsch at the Max Planck Institute for Quantum Optics in Garching, Germany, requires lasers that have state-of-the-art stabilities and power in the ultraviolet.

In the two-photon spectroscopy detection scheme, the hydrogen atoms are excited from the 1S to the 2S state by the simultaneous absorption of two photons, each with a frequency equal to half the resonant value. The researchers later apply an electric field

that mixes the 2S states with the nearby, short-lived 2P states, from which the atoms decay by emission of Lyman alpha radiation; the atoms are detected as a function of the laser detuning from resonance. The spectrum is shown in the figure on this page.

To understand the spectrum, you can mentally divide the atoms into two groups, depending on whether they absorbed photons traveling in the same or in the opposite direction. With absorption of same-direction photons, each atom experiences a momentum recoil and the absorption is recoil shifted by 6.7 MHz, as seen in the broad peak (blue circles) to the right of the origin in the figure. The Doppler width of the recoil-shifted signal is a measure of the temperature of the normal component of the gas.

If the atom absorbs oppositely-directed photons, there is no recoil shift or Doppler broadening, and one sees a peak centered on the resonance (the origin in the figure). Actually, this peak is not exactly on the resonance but is shifted slightly to the left by the presence of neighboring atoms, which change the atomic energy levels. The denser the atomic cloud, the greater the shift. The frequency shift is directly proportional to the density and has a value of 18 kHz for the density of the normal gas (around 10^{14} atoms/cm³).

The telltale sign of BEC (red circles) is the small peak that develops around 400 or 500 kHz to the left of the origin. It corresponds to atoms packed together with a very high density, some 20 times that in the normal gas. That's the signal that so elated the MIT researchers when it first appeared. Subsequently, they also found the signature of the Bose-Einstein condensate within the Doppler-broadened peak (see the red circles around 6–7 MHz).

Now that they have achieved their goal, Greytak, Kleppner and company won't rest on their laurels for long. The first item on their agenda is to see if they can get the condensate to live longer than five seconds. It decays primarily by spin relaxation. That's the disadvantage of a scheme with spin-up atoms, which are more susceptible than their opposites to having their spins flipped during collisions and then escaping from the trap. Because the relaxation rate increases with density, the MIT researchers will try to cool along a different path in the density-temperature plane to see if they can form a condensate at a lower density, which of necessity will require a lower temperature.

What's to be learned

In the three years since BEC was achieved in rubidium, sodium and lith-

ium atoms, a number of groups have done an amazing variety of experiments—demonstrating atom lasers, studying the interaction of two condensates, exploring the regime of second sound and so forth. BEC researchers now have one more, qualitatively different condensate to play with. For example, Bose–Einstein condensates in hydrogen might offer more promise for exploring effects that depend on large numbers of atoms, because hydrogen atoms do not have to be laser cooled, a process that grows more inefficient as the number of atoms increases. Hydrogen condensates should also allow precise comparison with many-body theories because the hydrogen interactions are so well known from exact theoretical calculations. However, such precise tests are increasingly available for condensates in the alkalis, because the theorists, no doubt stimulated by the recent progress, now have an excellent handle on the interactions in those atoms as well.

Greytak mentioned that the atoms

excited from the hydrogen condensate by the absorption of two copropagating photons pick up enough momentum to be ejected with low divergence, so that they might provide a narrow, intense beam of coherent atoms. (This has recently been done with sodium atoms from a condensate.) The hydrogen system also lends itself to high-resolution spectroscopy, with possible applications to metrology. Hänsch told us that a hydrogen Bose–Einstein condensate has potential as a fountain of cold hydrogen atoms, in which the resolution of the 1S–2S two-photon resonance could approach the natural linewidth of 1.3 Hz. Finally, the MIT researchers hope to use the low-temperature gas to continue work they have already begun, exploring the interactions of ultracold atoms with solid or liquid surfaces.

Of course, superconductors and superfluids are also examples of Bose–Einstein condensates, albeit in much more strongly interacting systems. One challenge for the future is to see a Bose gas act as a superfluid in the

sense of having persistent currents.

BARBARA GOSS LEVI

References

1. “Cold Collision Frequency Shift of the 1S–2S Transition in Hydrogen,” T. C. Killian, D. G. Fried, L. Willmann, D. Landhuis, S. C. Moss, T. J. Greytak, D. Kleppner, <http://web.mit.edu/physics/greytak-kleppner>.
2. “Bose–Einstein Condensation of Atomic Hydrogen,” D. G. Fried, T. C. Killian, L. Willmann, D. Landhuis, S. C. Moss, D. Kleppner, T. J. Greytak, <http://web.mit.edu/physics/greytak-kleppner>.
3. M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, E. A. Cornell, *Science* **269**, 198 (1995).
4. K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. Van Druten, D. S. Durfee, D. M. Kurn, W. Ketterle, *Phys. Rev. Lett.* **75**, 3969 (1995).
5. C. C. Bradley, C. A. Sackett, R. G. Hulet, *Phys. Rev. Lett.* **78**, 985 (1997).
6. H. F. Hess, *Phys. Rev. B* **34**, 3476 (1986).
7. I. A. Yu, J. M. Doyle, J. C. Sandberg, C. L. Cesar, D. Kleppner, T. J. Greytak, *Phys. Rev. Lett.* **71**, 1589 (1993).

Giant Air Shower Array Shows Cosmic-Ray Spectrum Violating Greisen Cutoff

For almost nine years, the Akeno Giant Air Shower Array in Japan has been accumulating data on the most energetic cosmic rays. AGASA, with its 111 scintillation detectors deployed over 100 km², is by far the world’s largest air shower array. (See *PHYSICS TODAY*, January 1998, page 31.) This collaboration of 14 Japanese institutions is led by Masahiro Teshima (University of Tokyo). The recent publication¹ of its observations through October 1997 appears to confirm a provocative astrophysical paradox: How can it be that the cosmic-ray energy spectrum is extending beyond 10²⁰ electron volts without any clear sign of a cutoff?

In 1966, not long after the discovery of the 3 K cosmic microwave background (CMB), Kenneth Greisen at Cornell pointed out that this ubiquitous swarm of low-energy photons must impose a strict upper limit on the cosmic-energy spectrum. Above a threshold energy of about 5×10^{19} eV, a proton plowing its way through the cosmic microwave background would be producing pions (and e^+e^- pairs) in

▶ The highest-energy cosmic rays appear to be thumbing their noses at what was thought to be an inviolable upper limit.

collisions with the low-energy photons at such a rate that it could not maintain itself above the threshold energy for more than a few tens of megaparsecs. But the only plausible astrophysical sources of such ultrahigh-energy protons are radio-loud quasars and active galactic nuclei of a kind that are simply not found within 100 Mpc of us. (One Mpc is about 3 million light-years. The Andromeda galaxy, our nearest full-grown neighbor, is about 1 Mpc away.)

This abrupt end predicted for the cosmic-ray spectrum has come to be called the Greisen-Zatsepin-Kuzmin (GZK) cutoff, because it was independently pointed out,

also in 1966, by Georgi Zatsepin and Vadim Kuzmin in the Soviet Union. One can’t get around the GZK cutoff by assuming that the highest-energy cosmic-ray primaries are really heavier nuclei rather than protons. Such nuclei would indeed have higher photopion-production thresholds, but too few would survive photodissociation over a long journey through the CMB.

Where’s the cutoff?

So why does the newly published AGASA high-energy spectrum, repro-

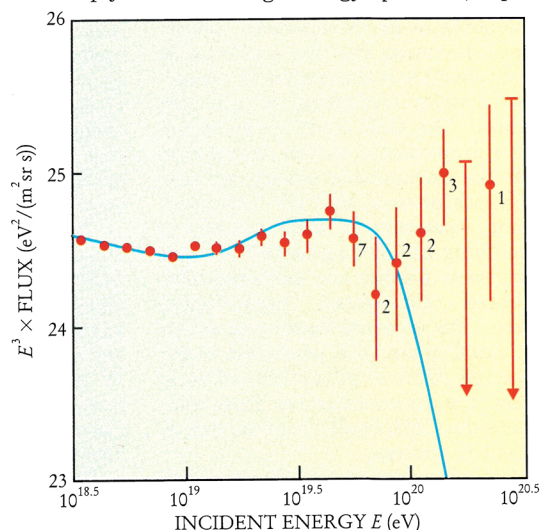


FIGURE 1. ENERGY SPECTRUM of high-energy cosmic rays observed by the AGASA shower array. The vertical axis is multiplied by E^3 .

The blue curve indicates the expected GZK cutoff, which the data seem to ignore. The highest energy data points are labeled with the observed number of events. The arrows indicate upper limits. (Adapted from ref. 1.)