Uncertain outlook

Besides the high-energy production of H in flight, researchers have proposed a number of schemes to yield the antiatoms at rest.[3] But the future of antihydrogen research at CERN is clouded by the closing of LEAR, scheduled for the end of 1996. LEAR is currently the favored source for the low-energy antiprotrons needed for most antihydrogen production schemes.

The last experiment to run on LEAR will be conducted by a group led by Gerald Gabrielse from Harvard University. The group includes researchers from Harvard, the University of Bonn, Seoul National University and Mount Holyoke College. In this last-ditch effort, Gabrielse told us that the collaboration will attempt to produce antihydrogen, although "it will be a stretch." Gabrielse and his colleagues have already succeeded in trapping up to 2×10^5 antiprotons[4] (see PHYSICS TODAY, July 1990, page 17) and, independently, up to 3.5×10^4 positrons[5] at 4.2 K in a Penning trap. (Using the antiproton trap, Gabrielse and his colleagues have demonstrated that the masses of the proton and antiproton agree to one part in 10^9, the most stringent test of *CPT* invariance performed to date on baryons.) The trick to producing antihydrogen is to store both species simultaneously in nested Penning traps, nudge the two clouds of particles together and get the antiprotons and positrons to combine.

If Gabrielse and his colleagues succeed in producing and trapping antihydrogen atoms, would that be the world's last look at them? Can one see a future for precision *CPT* tests on antimatter? One hope is to keep a low-energy antiproton capability at CERN. Among those with strong interest in antiprotons is Michael Holzscheiter of Los Alamos National Laboratory. His collaboration, like that of Gabrielse, has aspirations of producing antihydrogen; working at CERN, they have trapped, cooled and stored more than one million antiprotons in a large-scale Penning trap. Holzscheiter told us that researchers at CERN have come up with a plan to produce low energy antiprotons at CERN without using LEAR. The plan involves reconfiguring the antiproton accumulator, which is now an intermediate step in the cooling and storing of the antiprotons. A CERN study group has estimated that this plan would have a capital cost of about seven million Swiss francs, but would need only about one million francs to operate each year, compared to LEAR's annual operating expenses of about 17 million francs.

Another possibility is to use Fermilab, which has an antiproton beam of much higher intensity than CERN's, but one would have to build a new storage ring in which to cool the antiproton beam as it decelerates. Brookhaven National Laboratory also has an antiproton beam, but Holzscheiter feels that the beam is quite weak and diffuse. In the future, low-energy antiprotons could be available in Japan, as an adjunct (like LEAR) to a proposed, but not yet approved, 50-GeV proton synchrotron.

BARBARA GOSS LEVI

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Experimenters Produce New Bose–Einstein Condensate(s) and Possible Puzzles for Theorists

Three different systems of bosonic alkali atoms have now been cooled well into their respective quantum degenerate regimes. Two clearly exhibit Bose–Einstein condensation, whereas the third poses challenges to experimenters and theorists alike.

If the creation of a gaseous Bose–Einstein condensate in Boulder, Colorado, last summer marked the opening of a door to a new world of physics—the realm of weakly interacting, quantum degenerate atomic gases—then today we have unlocked multiple entrances to that domain. Furthermore, each entrance has a different architecture and looks out across a unique landscape.

Recall that the initial observation of Bose–Einstein condensation (BEC) in atomic gases by the group led by Carl Wieman and Eric Cornell (JILA, National Institute of Standards and Technology and University of Colorado, Boulder) was made with rubidium-87 atoms in a magnetic trap designed with rotating fields, the rotation serving to eliminate a "hole" at the coldest point of the trap.[1] (See the story in PHYSICS TODAY, August 1995, page 17.) The second definitive observation of BEC was achieved in October in a system of sodium atoms by Wolfgang Ketterle and coworkers at MIT.[2] This group used a laser beam to plug the hole in the trap. Their data are qualitatively very similar to the Colorado group's (see the upper figure on page 19) and, in the words of Wieman, "their results are rock solid." Added Cornell, "They can make their condensates very quickly and the condensates are *huge*. They're in an excellent position for doing science on these materials."

Earlier, hot on the heels of the Colorado announcement in July, a group at Rice University led by Randall G. Hulet reported evidence of a condensate in a system of lithium-7 atoms.[3] The interpretation of these results remains hotly debated because the experimental data are less conclusive and less direct. Hulet told PHYSICS TODAY, "While we are confident that we have observed a highly degenerate Bose gas, we agree that we have not unambiguously demonstrated the presence of BEC in our system." Meanwhile, theorists are working to understand what could be happening in a system of ^{7}Li as cold and compact as has been produced—the conventional wisdom had long been that, because of the attractive interatomic interactions, a condensate could not form in such a system.

BEC in sodium

When the race to BEC was won, Ketterle's group was a tantalizing one order of magnitude away from the finish line in phase space. "The problem," Ketterle explained, "was probably vibrations, which caused heating of atoms and loss of atoms." If the laser beam they used to plug the hole in their trap moved relative to the magnetic fields that form the walls of the trap, then the motion of the beam would "stir" the atoms. (See lower figure on page 19.) To counteract this effect, the researchers eliminated a vacuum pump that was causing vibrations and shielded the laser beam from air turbulence. They also decided to cool the atoms as fast as possible, to minimize whatever heating remained, even though doing so could lead to a denser and hence a less-stable condensate. (Indeed, their condensates had lifetimes of only about 1 second.)

The MIT researchers' success at rapid cooling became a major feature of their results: Their high production rate of condensed atoms (see PHYSICS TODAY, December 1995, page 9) allows them to take data about 30 times faster than the other groups, on about 300 times more condensate than the Colorado group. This ability will be important in further studies of the condensate, Ketterle explained: "Now we want to study properties of the condensate, for example by plotting a property of the condensate versus temperature, number of atoms and so on. This involves much more data taking and some studies would be almost impossible at a repetition rate of one shot every five minutes."

The unique geometry of the MIT trap also means that condensates are actually produced in pairs, one in each minimum of the trap's potential. The group studied the effect of moving the laser slightly off center, which greatly alters the shape of the trap's minimum and hence the shape of any condensate formed. As expected, above the transition point the velocity distributions remained spherical, indicating a classical gas in thermal equilibrium. For condensates, however, shifting the plug's location changed the velocity distributions, which depend on the shape of the trapping potential. The potential in the MIT trap is not known as accurately as the purely magnetic traps, making quantitative modeling more difficult for theorists.

The presence of two condensates has some theorists intrigued by the possibility of interference effects. The observation of interference fringes might only require somewhat colder temperatures and higher optical resolution. Another possibility is tunneling between the two condensates—analogous to a Josephson junction. However, the current design is not suited to such studies, Ketterle said, because modifing the plug to bring the two condensates closer together makes the trap leaky.

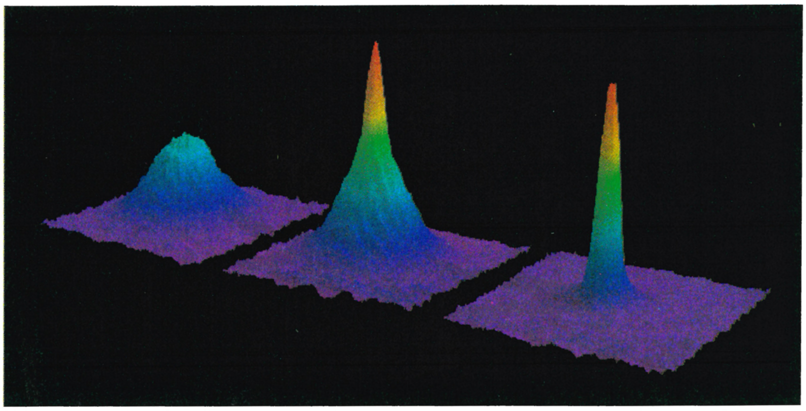
Degeneracy in lithium-7

Hulet's group has sidestepped the problems of leaky traps by using a design that relies on permanent magnets to produce a parabolic trapping potential. This configuration has the advantage that there is inherently no hole—the magnetic field is nonzero everywhere near the center of the trap. In addition, the group achieves a very good vacuum, making loss rates from the trap due to collisions with background atoms very low and hence allowing the Li atoms to be evaporatively cooled for times as long as minutes. Such a long evaporative cooling time is necessary because the trap's parabolic potential allows only a slow rate of evaporative cooling.

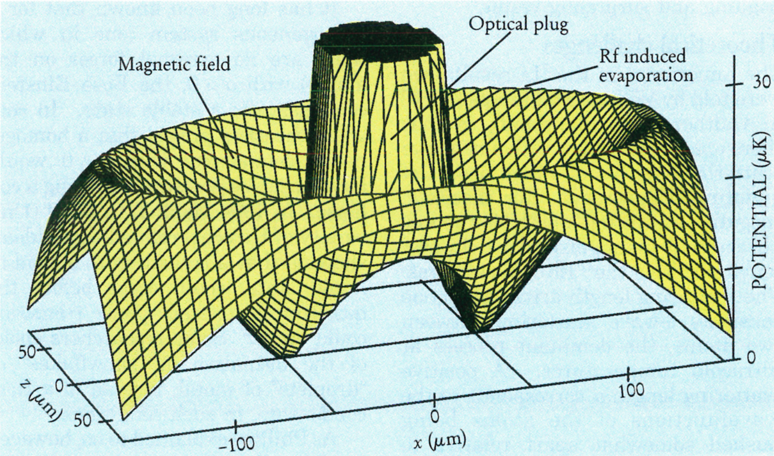
In this way, Hulet's group has succeeded in cooling the Li atoms to well below the quantum degenerate regime—the regime for which the de Broglie wavelength of individual atoms is larger than the typical distance between atoms. In published results[3] the group reports achieving phase-space densities greater than 10 times the critical density for an ideal gas—that is, 10 times the density at which one would expect the BEC phase transition to occur in an ideal gas. In results taken since then, Hulet told us, "We've now measured clouds whose sizes indicate temperatures as low as 17 nK. The corresponding critical parameters are as much as 200 times beyond what should be required for BEC."

Nevertheless the results remain "evidence for" and not "observation of" BEC in ^{7}Li. The problem is that the fields of the trap's permanent magnets cannot be "turned off," thereby ruling out the type of velocity distribution measurements that were key to the Rb and Na results. Hulet's group is limited to making direct observations of the density profile of the trapped gas cloud with a laser probe.

In their initial publication,[3] the Rice



VELOCITY DISTRIBUTIONS OF SODIUM ATOMS in ultracold clouds above the condensation point (left), just after condensation has begun at about 2 microkelvin (middle) and when essentially a pure condensate remains (right). Similar to the original demonstration of BEC in rubidium, these distributions are obtained by turning off the trap fields, allowing the clouds to expand freely for 6 milliseconds and then imaging the cloud with a laser probe. (Image courtesy of Dallin Durfee, MIT.)

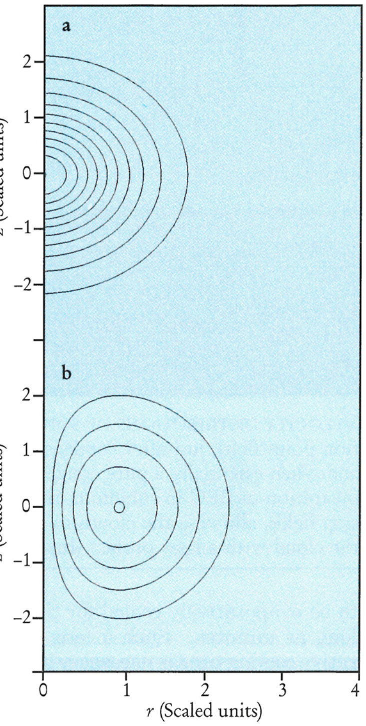


THE UNUSUAL GEOMETRY of the MIT trap is produced by three competing processes. Magnetic fields produce the rising walls of the trap. A detuned laser beam running through the center of the trap produces an "optical plug" by repelling atoms and thus preventing them from escaping where the magnetic fields drop to zero. A tunable rf field flips atoms' spins at a certain height up the walls, effectively turning the potential over at that point, creating a lip over which the hottest atoms can evaporatively escape. Note that the trap has two minima. (Adapted from ref. 2.)

researchers reported that at temperatures and densities that were too warm and dilute for quantum degeneracy, they saw a simple shadow of the gas cloud. Within the quantum degenerate regime, the shadow was smaller and in addition a halo of light appeared around it. The group interpreted this ring of light as being diffraction of the probe beam from a compact Bose–Einstein condensate. The data are inconclusive, however, for the presence of the ring depends in part on details of their imaging system; it is not elementary diffraction from a small object. In addition, Cornell told us that his Colorado group saw similar rings in early (unpublished) studies of their Rb system. When they later achieved their definitive observations of BEC, they deduced that not all of their ring observations corresponded to conditions that subsequently showed BEC.

More recently, Hulet told us, his group has improved the imaging system, eliminating the ring artifacts but confirming more directly, he says, that the clouds are extremely small—having a Gaussian radius of about 10 μm. Although this size (along with the density and temperature data) implies that the degenerate regime has been achieved, it is *larger* than the size (about 3 μm) of the ground state of the trap potential. Also, they have observed no evidence of a phase transition.

Cornell, who with Wieman is skeptical of Hulet's published evidence for BEC, nevertheless said that "If they really have these very cold degenerate clouds, that's very exciting—particularly if there's no appearance of a condensate, because that would be an intriguing and surprising result."



GROUND STATE AND VORTEX WAVEFUNCTIONS predicted for 1000 ^{7}Li atoms. The contours indicate linearly increasing values of the wavefunction. **a:** The ground state rises to a high density at the center of the trap. If a few hundred more atoms are added, the state shrinks in size and becomes unstable. **b:** In a vortex state the atoms rotate coherently about the z axis and the peak density is much lower than for the ground state. (Adapted from ref. 7.)

Theoretical challenges

The importance of the ^{7}Li results, we were told by William D. Phillips (NIST in Gaithersburg, Maryland), is that "here one has a system with a negative scattering length and a high degree of quantum degeneracy." For theorists, "negative scattering length" is the key phrase that distinguishes the ^{7}Li system from either the ^{87}Rb or Na systems. The scattering length arises when one considers s-wave scattering between two atoms, the dominant process at ultracold temperatures. A positive scattering length a corresponds to the wavefunctions of the atoms being pushed somewhat apart relative to point scattering; at large distances it looks like hard scattering of spheres with radius a. A negative scattering length corresponds to the wavefunctions being pulled together by a corresponding amount. Thus positive a corresponds to an effective repulsion, negative to an attraction.

It has long been known that for a homogeneous system (one in which there are no external forces on the atoms) with $a > 0$, the Bose–Einstein condensate is a stable state. In contrast, theorists proved that a homogeneous condensate with $a < 0$ would have negative pressure, implying a collapse. In 1994 Henk T. C. Stoof (University of Utrecht) refined these ideas, showing that a transition to a solid or liquid state would occur before the quantum degeneracy phase transition could occur.[4] Some researchers spoke of the formation of "snowflakes" or "droplets" of metal, instead of a Bose condensate, in such conditions.

As Phillips explained to us, however, a solid or liquid is not going to form in the experimental situations. The first step in such a process would be the formation of small molecules, and a molecule "is likely to be lost from the trap, so there is little chance of forming a macroscopic crystal or droplet." Theorist Keith Burnett (University of Oxford) talks of a rapid contraction of any condensate formed, with a corresponding rise of reactions that cause ejection of hot atoms (and molecules) from the trap.

Nevertheless, hope remained that in an experiment a condensate could still form. Confinement of atoms within a trap breaks the theorist's assumption of homogeneity and provides an effective pressure that can counteract the effect of the negative scattering length. The pressure arises from simple particle-in-a-box quantum mechanics: the zero-point energy.

Peter A. Ruprecht, Murray J. Holland and Burnett (all then at Oxford) and Mark Edwards (Georgia Southern University) put these ideas on a more quantitative footing by numerically solving the nonlinear Schrödinger equation for atoms in harmonic traps and Yuri Kagan, Gori Shylapnikov and Jook T. M. Walraven (University of Amsterdam) also studied the stability of such a condensate.[5] Gordon Baym and Christopher Pethick (University of Illinois at Urbana–Champaign) obtained approximate analytic solutions.[6] Numerous other theorists are performing similar studies. All the theory points to roughly the same conclusion: A small number of atoms with $a < 0$ can form a condensate, but as more atoms are added the condensate shrinks in size and eventually a critical number is reached at which point the condensate collapses. But for ^{7}Li atoms with parameters corresponding to the Rice University experiment, the critical number appears to be about 1300 to 1500—well below the largest numbers reported by Hulet and company to be in degenerate clouds.

Vortex states?

What possible explanations are there? An intriguing speculation is that the Rice results might correspond to condensation into a state other than the ground state. One candidate would be a vortex state—a type of state that is well-known in superfluid helium. Roughly speaking, a vortex state corresponds to a coherent rotation, each atom circling the vortex with the same quantized angular momentum. For a given number of atoms, a condensate in the vortex state would have higher energy and lower density than one in the ground state, and thus a vortex state should be stable for larger numbers of atoms.[7] (See figure above.) Hulet pointed out that a vortex state might explain the large size of the degenerate clouds his group has observed.

The idea that condensates of vortex states (or other states above the ground state) could explain Hulet's results has many potential problems, however, and remains highly speculative. Only time and more experimental data will tell.

GRAHAM P. COLLINS

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Labs Demonstrate Logic Gates for Quantum Computation

After years of just writing down Hamiltonians and algorithms, quantum computer enthusiasts have begun creating logic gates in the lab. Where will it end?

Since the early 1980s, theoreticians of various stripes have been carrying on a lively discussion about how and why one might build a quantum mechanical computer. (See the article by Charles H. Bennett, PHYSICS TODAY, October 1995, page 24.) Now the appearance of two back-to-back papers in the 18 December issue of *Physical Review Letters*, reporting the demonstration of experimental "quantum logic gates," has focused the discussion onto the physics laboratory.

In one of these papers,[1] Christopher Monroe, David Wineland and coworkers at the National Institute of Standards and Technology facility in Boulder, Colorado, report the operation of a quantum logic gate that couples the hyperfine splitting of a single trapped ion to its oscillation modes in the ion trap. The device performs the function of a "controlled-NOT" Boolean logic gate on a pair of binary input bits specified by the oscillation mode and the hyperfine state.

In the adjacent paper,[2] Jeffrey Kimble's quantum optics group at Caltech reports the demonstration of large nonlinear phase shifts for photon pairs coupled by a single atom in a quantum electrodynamic cavity. Such a device would serve as a "quantum phase gate," exhibiting an optical phase shift that depends strongly on the binary input bits embodied by the polarization states of the two incoming photons.

We can label the two states of a binary information bit $|0\rangle$ and $|1\rangle$. A controlled-NOT gate, operating on two input bits (called the control bit and the target bit) will flip the target bit if, and only if, the control bit is $|1\rangle$. Such a two-bit gate, coupled with simple single-bit rotations, could serve as the universal gate for a quantum computer. So could a quantum phase gate, which phase-shifts the input states if, and only if, both are $|1\rangle$. Whether it's more efficient to employ such phase gates in place of controlled-NOT gates depends on the kind of computation one wants to do.

In a quantum computer, the input state can be in any coherent superposition of the basis states. That is its essential distinction from a classical computer, and it's what would give a quantum computer unique capabilities for doing massively parallel computations—if the coherence between the superposed states can be adequately preserved. Quantum binary bits have come to be called "qubits" (pronounced like the biblical unit of length).

Lone ion vibrating in a trap

The Boulder group's logic gate starts with a single Be^+ ion sitting in a radio-frequency ion trap and made so cold that its motion can occupy only the first two quantized harmonic-oscillator modes along the trap's axis. These lowest vibrational states, separated by 11 MHz, serve as the $|0_V\rangle$ and $|1_V\rangle$ states of the gate's control qubit. The target qubit is the hyperfine substate of the ion's s-wave ground state. The lower-lying substate $|0_H\rangle$, with the valence electron's spin antiparallel to the spin of the nucleus, is separated from the substate $|1_H\rangle$, with the spins parallel, by an energy that corresponds to 1.250 GHz (called the carrier frequency).

Thus the two-qubit system has four different energy levels: $|0_V\rangle|0_H\rangle$, $|1_V\rangle|0_H\rangle$, $|0_V\rangle|1_H\rangle$ and $|1_V\rangle|1_H\rangle$. Irradiating the trapped ion precisely at the carrier frequency induces transitions between the two hyperfine states *without* changing the trap-oscillation mode. But by shifting the radiation frequency 11 MHz to the red or blue, one can simultaneously flip the hyperfine and oscillation states. While it's being irradiated at a given transition frequency, the atom cycles back and forth coherently between bit states at the so-called Rabi nutation frequency, which depends on the intensity of the perturbing radiation. If one stops irradiating at an arbitrary moment, the qubit ends up in an arbitrary coherent superposition of its two states. To get a complete, clean flip requires a radiation pulse that lasts for precisely half a Rabi cycle (a "π pulse"), which in this experiment is on the order of a few microseconds.

Even though the gigahertz transition frequencies are in the microwave regime, the Boulder group operates the gate by means of optical fields. A pair of laser beams with a precisely tunable frequency separation induces stimulated Raman transitions when the difference frequency is tuned to the appropriate transition frequency. The strong spatial gradient of the optical field provides the necessary coupling between the ion's internal state and its external motion.

After setting the initial two-qubit state at will to any one of the four energy levels, or any desired coherent superposition of them, the Boulder group operates the controlled-NOT logic gate by applying a sequence of three Raman radiation pulses to the trapped ion:

(1) a $\pi/2$ pulse with the difference between the two lasers tuned to the carrier frequency,

(2) a 2π pulse at a difference frequency that would induce a transition between the $|1_V\rangle|1_H\rangle$ state and a convenient "auxiliary" state separated from the ground state by a 3-MHz Zeeman splitting, and finally

(3) a repeat of the first $\pi/2$ pulse, but this time phase-shifted by π relative to step 1.

A $\pi/2$ carrier pulse lasts precisely ¼ of a Rabi cycle. It would convert a pure hyperfine state into a coherent equal superposition of $|0_H\rangle$ and $|1_H\rangle$. But these pulses (steps 1 and 3) have no effect on the ion's vibration mode. Step 2, by way of an excursion to the auxiliary state and back, simply reverses the sign of any component that happens to be in the $|1_V\rangle|1_H\rangle$ state after step 1.

Thus the three-pulse sequence performs the function of a controlled-NOT gate: If the control bit is in the $|0_V\rangle$ state, pulse 2 has no effect whatsoever and pulses 1 and 3 simply cancel each other out to leave the target hyperfine bit in its initial state. But if the control bit is $|1_V\rangle$, step 2 changes the sign of the state's $|1_V\rangle$ component. Thus, instead of canceling each other out, steps