Antihydrogen Makes a Fleeting Debut

Like a high-profile wedding of movie stars, the recent mating of positrons with antiprotons at CERN commanded worldwide attention. But even by Hollywood standards the marriage was short-lived: The antihydrogen lasted a mere 37 nanoseconds before the positrons were annihilated by collisions with electrons in the detector. That time was too short and the number of antiatoms formed was too few for researchers to conduct high-precision comparisons between hydrogen and its antimatter counterpart. Such studies would tell us whether nature obeys *CPT* invariance, that is, whether phenomena remain invariant under the simultaneous operations of charge conjugation, parity inversion and time reversal, and whether matter and antimatter feel the same pull of gravity. The recent experiment at CERN fired imaginations by demonstrating the reality of antihydrogen, but antiatoms must be produced nearly at rest, rather than in flight as in the CERN experiment, before they can be studied in detail.

> Now that antihydrogen atoms have made their first appearance, researchers are hoping for further visits that will reveal more fully the traits of this rare species.

Matchmaking

The experiment was suggested four years ago by a group led by Charles Munger, who was then a postdoc at the Stanford Linear Accelerator Center. The main idea is that when an antiproton passes through the Coulomb field of a nucleus, it can produce an electron–positron pair. A small fraction of the time, the positron just happens to have nearly the same velocity as the incident antiproton and will be captured by it. If the process occurs in near-vacuum conditions, the two will continue to travel as a bound antihydrogen atom.

Munger, together with Stanley Brodsky of SLAC and Ivan Schmidt of Santa Maria University in Valparaiso, Chile, calculated that the rate for this process[1] was large enough to enable antihydrogen to be detected using the Fermi National Accelerator Laboratory's antiproton accumulator and the hydrogen gas-jet target that had been built for another experiment.

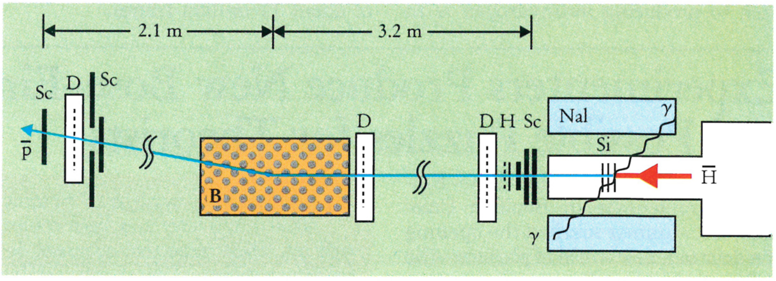
A collaboration led by Munger, which included groups from the University of California at Irvine, Pennsylvania State University and Fermilab, submitted a proposal for the experiment to Fermilab. Although the proposal was accepted, the collaboration will not have a chance to take data at Fermilab until July; the experiment requires the accelerator to run in the fixed target mode, and for the last few years, the Fermilab accelerator has been operating in the collider mode to search for the top quark.

In the meantime, a collaboration of European institutions was given time at CERN to try the same experiment.[2] The collaboration included researchers from institutions in Germany, Italy and Switzerland: KFA in Jülich, Erlangen–Nürnberg University, GSI in Darmstadt, the University of Münster, Genoa University, the National Laboratory for Nuclear Physics in Genoa and CERN. This group formed antihydrogen by aiming antiprotrons from CERN's Low Energy Antiproton Ring at a target of xenon atoms. The target xenon atoms were shot from a gas-jet nozzle across the path of the antiprotons as they circulated around LEAR.

Once formed, antihydrogen atoms traveled about ten meters from the interaction region to a set of silicon detectors surrounded by sodium iodide calorimeters. See the figure above. The positrons from any antihydrogen atoms were stopped by encounters with electrons in this detector, and their presence registered by the characteristic annihilation photons. Additional instruments down the line determined such properties of the stripped antiprotons as the particle trajectory, time of flight, magnetic deflection and energy loss.

By applying certain criteria to the 300 000 triggers in their experiment, the collaboration at CERN, which is led by Walter Oelert of KFA in Jülich, selected 11 events that had the signatures expected of antihydrogen atoms. Two of those were attributable to background, and so the observed production rate coincided exactly with the theoretical expectation of nine events. However, the most one can really say is that the two rates are consistent, in view of the 30% statistical error and the roughly 50% uncertainty in the product of beam intensity and thickness of the cluster target.

Oelert does not expect that his team will attempt to produce any more antihydrogen atoms. The job of verifying their work should fall to the Fermilab group, for which David Christian is now the spokesperson. Christian told us that Fermilab has a new gas-jet target; made by the same Genoa University team that built the one at CERN. Because the antiproton beam at Fermilab is much more intense than the LEAR beam, the Fermilab experiment should produce on the order of a thousand antihydrogen atoms, enough to give a statistically better check on the production cross section. If the researchers could find a way to form as many as 10 000 antiatoms, Christian said, they could begin to do some spectroscopic measurements, but with fairly low precision.



PATH OF ANTIHYDROGEN. Produced by collisions in LEAR (at the right), an antihydrogen atom (red line) travels ten meters to a silicon counter (Si), where positrons annihilate with electrons and the characteristic photon pair is detected in the sodium iodide calorimeter (NaI). The antiproton (blue line) continues through scintillators (Sc), delay wire chambers (D), a scintillating fiber hodoscope (H) and a magnetic dipole field (B). Cuts made on the properties measured by the various instruments eliminate all but the antihydrogen events. (Adapted from ref. 2.)

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.

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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,