quick study

Slow antihydrogen

Gerald Gabrielse

The quest to precisely compare cold antihydrogen and hydrogen atoms should enable physicists to test our understanding of one of reality's fundamental symmetries.

Gerald Gabrielse is the Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts and is the spokesperson for the ATRAP collaboration at CERN in Geneva.

Angels and Demons, a bestselling book and popular movie, describes the theft of "trapped antimatter." Not specified is whether what is trapped is the charged antimatter particles that my colleagues and I are proud to have first trapped at CERN or the neutral antimatter atoms that we hope to soon trap. In the story, sinister folks threaten to annihilate the trapped antimatter to blow up the Vatican and the cardinals assembled there to select a pope. The same distorted lens with which author Dan Brown disfigured the Roman Catholic Church in *The Da Vinci Code* was focused on our cold antiproton and antihydrogen research program in *Angels and Demons*. Brown made his millions untroubled by the fact that the simultaneous annihilation of all the antiprotons ever made would not release enough energy to boil a pot of tea. The movie's camera zooms in on a part of CERN where no antimatter particles circulate and no antimatter will be trapped—the Large Hadron Collider (LHC).

The myth and the science

Trapped antimatter as popular mythology was not on my mind when, 23 years ago, I first asked CERN for a chance to slow, trap, and cool their antiprotons. The first goal of the TRAP collaboration, which I was privileged to lead, was to precisely compare the charge-to-mass ratios of the antiproton and proton. We demonstrated methods to accumulate cold antiprotons and realized the comparison with a precision of 9 parts in 10^{11}. The second goal was to produce and study cold antihydrogen; when that goal became primary, we renamed the collaboration ATRAP. In view of initial skepticism at CERN about accumulating antiprotons 10 orders of magnitude lower in energy than ever before obtained, who could have predicted that CERN would eventually build a storage ring for cold antihydrogen studies and that four international collaborations would join the hunt for cold antihydrogen?

Those collaborations—ATRAP, ALPHA, ASACUSA, and AEGIS—now encounter their own angels and demons. The angels are the skilled accelerator physicists at CERN who built and operate the antiproton decelerator (AD) storage ring. Every 100 seconds, that tiny relative of the LHC provides 30 million 5-MeV antiprotons in a short pulse. The demons obstructing ATRAP and ALPHA are whatever is keeping the antihydrogen atoms that they are producing from moving slowly enough to be trapped efficiently and from decaying to their ground state before they escape the apparatus. (ASACUSA hopes to make antihydrogen soon, and AEGIS is designing its first apparatus.)

The scientific goal of cold antihydrogen studies is to precisely compare antihydrogen and hydrogen atoms to check if their structure or gravitational interactions differ. They will not if, as most physicists expect, reality is invariant under *CPT* transformations: interchange of particles and antiparticles (charge conjugation, *C*), inversion of the three spatial directions (parity, *P*), and reversal of motion (time reversal, *T*). Such invariance is an unavoidable consequence of the most successful theories in physics, axiomatic quantum field theories that are invariant under Lorentz transformations.

Simply assuming *CPT* invariance seems incautious since gravity has not been successfully incorporated into a quantum field theory. Also, we physicists once thought incorrectly that reality was invariant under *P*, and later incorrectly that it was invariant under *CP*. In the end, God decides and we measure. Precise and interpretable comparisons of the simplest atoms of antimatter and matter should produce the most stringent test of *CPT* symmetry with lepton and baryon particles. It would be wonderful if *CPT* violation were to be detected and contribute something to an explanation of the imbalance of matter and antimatter in the universe.

Two methods form slow antihydrogen

The building blocks of ATRAP's apparatus, shown in figure 1, are similar to those of ALPHA. The antiprotons sent from the AD slow as they pass through a thin matter window and slow

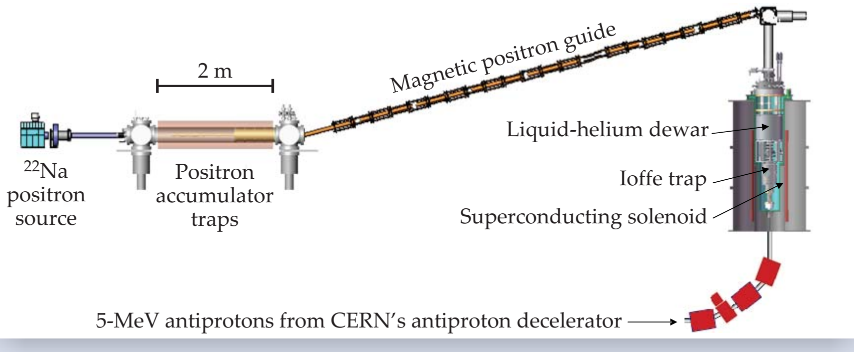

Figure 1. Key components of the ATRAP apparatus that accepts antiprotons from the antiproton decelerator at CERN and slows positrons from a sodium-22 source. The goal of the experiment is to trap and study cold antihydrogen atoms in the specially designed magnetic fields of the Ioffe trap.

as they interact with electrons, the only matter particles unable to annihilate them. The process is rapid enough that annihilation with nuclei is minimal. Those slowed charges are captured in Penning traps—potential wells made by applying voltages to hollow metal electrodes and applying a magnetic field along their axis (see figure 2)—where they cool by colliding with simultaneously trapped electrons. Positrons from the decay of sodium-22 collide with atoms in a column of decreasing gas density and end up similarly trapped in the low-gas-density end of a positron accumulator. Tens of millions of the positrons are transferred to the Penning traps (figure 2) in two bunches delivered between antiproton pulses.

Most slow antihydrogen atoms are produced in a nested Penning trap, a device that several of us invented to allow trapped charges with opposite signs to interact. Since a potential well for antiprotons is a potential hill for the oppositely charged positrons, a nested trap is a potential well for antiprotons inside of which is a shallower inverted well that confines positrons. The positrons emit synchrotron radiation and, within minutes in a 1-T magnetic field, come to thermal equilibrium with the surrounding apparatus. The heavier antiprotons cool by colliding with the cold positrons. Those that cool to just the right energy can collide with two positrons to form an antihydrogen atom. The spectator positron enables conservation of energy and momentum. Several years ago ATRAP and ATHENA (now disbanded) both observed antihydrogen atoms produced in that way.

The ATRAP group also demonstrated a second, laser-controlled method to produce slow antihydrogen atoms. Infrared and green lasers put cesium atoms into highly excited states. Those Cs atoms collide with trapped positrons to form excited positronium atoms, bound states of a positron and an electron. A few of those collide with trapped antiprotons to form antihydrogen. The laser frequencies determine the excited state of the antihydrogen because the binding energy of the Cs atoms is approximately transferred to the positronium and then to the antihydrogen. The antihydrogen formed should have the temperature of the antiprotons since the light positronium atom does not transfer much momentum to the heavier antiproton.

Traps for antihydrogen and beyond

My initial proposal to trap antihydrogen atoms arose from the expectation that antihydrogen atoms would always be scarce and would thus be most efficiently studied if kept from drifting out of the apparatus. As subsequently demonstrated with hydrogen, an atom with a magnetic moment can be confined where there is a minimum in the magnitude of a magnetic field. A Ioffe trap uses currents in racetrack coils and pinch coils, as shown in figure 2, to make the field minimum.

The ATRAP and ALPHA collaborations recently produced antihydrogen atoms within Ioffe traps. They are looking for evidence that trapped atoms are released and annihilate when the traps are turned off fast enough to nearly eliminate the background signals from cosmic rays. The groups have seen only the very occasional intriguing signal but hope to soon produce useful numbers of trapped antihydrogen atoms.

A significant challenge is that the strongest Ioffe traps can confine only atoms whose energy is lower than 0.5 K. The atoms produced so far seem to be moving too rapidly to be trapped efficiently, and the likelihood of losing excited antihydrogen atoms from the trap as they decay to lower states is not well understood. ATRAP and ALPHA are now carefully studying the temperatures, densities, and spatial distributions of cold antiproton and positron plasmas to learn how to produce colder atoms.

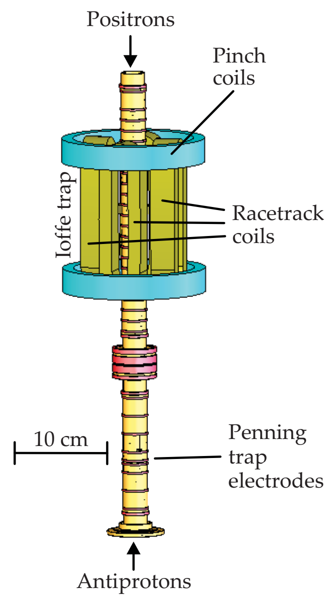

Figure 2. The traps of ATRAP. Suitably engineered electric and magnetic fields confine charged particles such as antiprotons and positrons in Penning traps. Antihydrogen forms when trapped antiprotons and positrons meet in a nested Penning trap whose electrodes are visible between the labeled racetrack coils. Trapping the antihydrogen requires the magnetic fields of a Ioffe trap generated with the indicated pinch and racetrack coils.

At ATRAP we are encouraged by three recent developments. First, we can now use electron and positron plasmas with temperatures approaching 1 K to cool antiprotons. If we could produce antihydrogen atoms at that temperature, a substantial fraction of them could be confined in a trap 0.5 K deep. Second, every hour as many as 5 million cold antiprotons and 100 million or more positrons are available for making antihydrogen. Third, we have recently demonstrated the sensitivity required to detect a single antimatter counterpart of H^- and H_2^+ ions, should a few of those be produced in the antihydrogen apparatus. The ALPHA group uses higher-temperature plasmas and many fewer antiprotons to form the atoms than ATRAP does, but attempts to trap atoms more frequently. ALPHA relies on position-sensitive detectors as well as upon a very rapid Ioffe-trap turn-off time to help distinguish potential antihydrogen signals from cosmic rays.

The newcomers to antihydrogen have big plans. The ASACUSA collaboration hopes to produce antihydrogen within a magnetic trap variation out of which atoms would leak for microwave spectroscopy. Meanwhile, AEGIS proposes interferometry to investigate the gravitational acceleration of 0.1-K antihydrogen atoms if they can be produced.

Everyone doing antihydrogen physics is excited about a possible 100-fold increase in the number of trapped antiprotons that the proposed ELENA upgrade to the AD at CERN would allow. More antihydrogen atoms, more rapid progress, and more precise studies of antihydrogen structure and gravity would certainly result if ELENA angels can be found amongst the funding demons.

Additional resources

▶ Homepages of the four collaborations hoping to study cold antihydrogen

ATRAP: http://hussle.harvard.edu/~atrap
ALPHA: http://alpha.web.cern.ch
ASACUSA: http://asacusa.web.cern.ch
AEGIS: http://aegis.web.cern.ch/aegis/home.html.

▶ G. Gabrielse, "Atoms Made Entirely of Antimatter: Two Methods Produce Slow Antihydrogen," *Adv. At. Mol. Opt. Phys.* **50**, 155 (2005).

The online version of this Quick Study provides additional references.