Low-energy atoms of antihydrogen will enable researchers to test a fundamental property of the universe

By Graham P. Collins

MAKING COLD ANTIMATTER

It is the nemesis of normal matter: antimatter. Like evil twins of ordinary particles, antimatter versions mirror their mundane counterparts in every way, except for having the opposite charge, and they promise violent annihilation if ever the twain should meet. Indeed, the conflagration of a single gram of antimatter particles merging with their normal matter siblings would release energy equivalent to about 40 kilotons of TNT, or enough to power nearly 5,000 households for a year.

Fortunately for our safety and unfortunately for our energy policy, antimatter is rare in the natural world. Some radioactive substances emit positrons, the antiparticles to electrons, and are used in PET (positron-emission tomography) scans. A small number of antiprotons constantly sleet down from space among cosmic rays. In addition, the giant showers of particles produced when a high-energy cosmic-ray particle strikes an atom in the atmosphere contain numerous antiparticles.

But when it comes to actual chunks of material, antimatter is simply not to be found. Even lone atoms of antimatter, or antiatoms, are not known to exist in nature. Yet theory suggests that the study of antiatoms could contribute unique insights into the laws of physics. So scientists have set about trying to manufacture their own. In recent years, they have devised clever technologies and enjoyed some success.

Particle physicists have been creating beams of antiprotons since 1955. That achievement came at the Bevatron accelerator at Lawrence Berkeley National Laboratory, by smashing protons into a piece of copper. The process is the reverse of annihilation—some of the pure energy of the collisions is converted into pairs of newly minted protons and antiprotons. Today Fermi National Laboratory in Batavia, Ill., takes antiprotons circulating in huge rings and collides them head-on with a similar beam of protons to study particle physics at extremely high energies.

The first antiatoms ever to exist were made in 1995 by scientists at CERN, the European laboratory for particle physics near Geneva. They arranged for a beam of antiprotons circulating in a storage ring to cross a jet of xenon atoms. Occasionally a collision produced an electron-positron pair, with the positron and antiproton flying off together and forming an antihydrogen atom. The team observed nine such antiatoms racing along at nearly the speed of light. A similar experiment at Fermilab in 1998 produced 57 antiatoms.

But such high-velocity antiatoms are not very useful. To study the properties of antiatoms more thoroughly, scientists want to hold them in an atom trap, which means they must slow them down and cool them to less than 0.5 kelvin. Two fiercely competitive research groups working at CERN have been pursuing that goal. The ATRAP collaboration, led by Gerald Gabrielse of Harvard University, sprang out of an earlier group (TRAP) that pioneered the capturing and cooling of

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antiprotons [see "Extremely Cold Antiprotons," by Gerald Gabrielse; Scientific American, December 1992]. ATHENA, a group led by Rolf Landua of CERN, joined the fray late in the game but in 2002 was the first (by a few weeks) to publish a research paper announcing detection of cold antihydrogen atoms. Another team, ASACUSA, is studying exotic helium atoms in which one electron is replaced by an antiproton.

Although some researchers hold out hope of one day using antimatter for propulsion [*see box on page 85*], the primary immediate goal of investigating antiparticles has to do with the study of what is called the CPT symmetry theorem, which relates the properties of a particle species with those of its antiparticle. The theory predicts that both should follow the same physical laws. Given enough trapped antiatoms, scientists hope to see if antihydrogen emits and absorbs light at exactly the same frequencies as hydrogen does. If CPT symmetry is obeyed, the two spectra should be identical.

Historically, symmetries related to CPT symmetry have a losing track record: each one has turned out to be violated by the real world. Every time that a symmetry prediction has been overturned, startled physicists have learned important new information about the properties of the fundamental particles and forces. Violation of CPT symmetry by antihydrogen would be the granddaddy of broken symmetries and would have major consequences for physicists' conceptions of reality.

To understand more precisely what CPT symmetry is and why it is so important, split it into the individual component parts that the three letters stand for: charge reversal, parity inversion and time reversal. Charge reversal is the replacement of all particles with antiparticles. Parity inversion is essentially reflection in a mirror (more exactly, it is inversion of space about a point). And time reversal means playing the "movie" of reality backward.

Saying that P symmetry is operating, or that nature is "invariant" under P symmetry, means that any physical process observed in a mirror still follows the same laws as the unreflected process. If you imagine yourself tossing a ball in the air in front of a mirror, P symmetry seems intuitively obvious. How could it not be obeyed in every process? Amazingly, as was discovered in 1956, P symmetry is broken by the weak nuclear interaction, which is involved in certain radioactive decays. Cobalt 60 decaying in reality looks different from decaying cobalt 60 viewed in a mirror. Like a person swinging a tennis racket in her *right* hand (whose reflection therefore is *left*-handed), the decay of cobalt 60 has an intrinsic handedness that is reversed by a mirror.

ATHENA APPARATUS at CERN near Geneva is one of two facilities that have been producing cold antihydrogen.

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Overview/The First Antiatoms

- **Antiparticles have a charge opposite to that of their corresponding particles, and if the two meet, they annihilate, releasing a large amount of energy. Recently physicists have succeeded in creating the first relatively slow-moving atoms of antimatter (antiatoms).**
- **In the future, these antiatoms—consisting of antihydrogen—could be used to test a fundamental property of the universe known as CPT symmetry. Even a tiny violation of CPT symmetry would be a profound discovery and would hint at new physics.**
- **So far, however, the antihydrogen atoms seem to have a temperature of about 2,400 kelvins—far hotter than the 0.5 K needed to trap them for studies of CPT. The next major goal is to produce antiatoms at still lower temperatures and in states suitable for spectroscopy.**

In many situations where P symmetry is broken, CP symmetry is nonetheless preserved. That is, a mirror image of an anticobalt atom behaves identically to a real cobalt atom. It is as if the antiperson is left-handed, so that her reflection is right-handed—the same as the original, unreflected person.

To physicists' amazement, in 1964 they learned that CP symmetry is also broken on rare occasions in certain processes. Despite its great rarity, broken CP symmetry might play a role in explaining the predominance of matter over antimatter in the universe [*see box on opposite page*].

That leaves CPT symmetry: the equivalent of what you would see if you watched a movie that starred antiparticles run backward in a mirror. CPT invariance means that the crazy reversed antimovie would follow exactly the same laws of physics as reality. If the behavior of the reversed antimovie differed in any way from that of reality, that difference would be a "violation" of CPT symmetry.

CPT symmetry has deep mathematical foundations. It is hardwired into the equations of quantum field theory that describe the fundamental particles and forces. For more than half a century, all of particle physics theory has been based on quantum field theory; the violation of CPT would signal its breakdown. Such a result would be a major clue to how to develop a theory of physics that goes beyond the Standard Model of particle physics.

Physicists have inferred from particle physics experiments involving unstable particles that any violation of CPT symmetry must be very small. In addition, when Gabrielse's TRAP group conducted experiments comparing trapped antiprotons with protons, they verified CPT symmetry for this class of particle to greater precision than anyone had previously achieved. But the search must go on, at ever finer levels of precision, for there are reasons to expect that CPT violation could happen at some smaller scale [see "The Search for Relativity Violations," by Alan Kostelecký; SCIENTIFIC AMERICAN, September 2004]. Hydrogen spectroscopy is very precise. If the same precision could be achieved with antihydrogen, a comparison of the two spectra would take physics well beyond the present CPT frontier for stable particles.

As well as violating CPT symmetry at times, antimatter might be affected by gravity differently than matter. It is not that antimatter would experience "antigravity" and be repelled by matter, as some people mistakenly think. Rather a tiny component of the force of gravity might be reversed for antimatter. Such a discovery would profoundly revise our understanding of gravity. Studies of charged antiparticles such as positrons and antiprotons are hopeless for examining the effects of gravity; perturbations caused by stray electric and magnetic fields are far too great. Conceivably, however, neutral antiatoms might be cooled to extremely low temperatures and observed freely falling, as has been done with laser-cooled regular atoms. Gravity experiments will be orders of magnitude more technically challenging than the CPT tests, however.

Anti-ingredients

TO MAKE the antihydrogen atoms needed for these experiments takes two ingredients—positrons and antiprotons, which are starkly different in their ease of manufacture. Positrons are comparatively simple to come by; numerous radioactive isotopes emit them in a process called beta decay. Antiprotons must be made out of whole cloth.

The experiments at CERN use the isotope sodium 22 as their source of positrons. A one-gram chunk of sodium 22 emits 200 trillion positrons every second. But those positrons are emitted with 550 kilo-electron volts of energy, equivalent to a temperature of six billion degrees Celsius. To be of use in making cold antihydrogen, they must be slowed down from their emission speed, nearly nine tenths the speed of light, to mere kilometers per second. The slowing is achieved by a series of different processes [*see box on next two pages*]. After about five minutes, the ATHENA group accumulates around 75 million positrons suspended by magnetic and electric fields in the high vacuum of a Penning trap (named after physicist Frans Michel Penning, who invented the design in 1936). ATRAP, in contrast, captures about five million positrons. The traps hold the positrons very securely: after an hour, an insignificant number of them are lost.

Because antiprotons are not produced by any convenient radioactive source, researchers have to create these antiparticles out of pure energy, which they do by firing protons into a metal target. This process produces, among other particles, a high-energy pulse of antiprotons. To make cold antihydrogen, the experimenters must slow down the antiprotons to a temperature similar to that of the positrons. Much the same technology that accelerates particle beams is used in reverse to perform the first stage of the deceleration process. Since 2000 this deceleration has been carried out by the Antiproton Decelerator at CERN.

Every minute and a half, the Antiproton Decelerator emits a pulse of about 20 million antiprotons. They travel at a mere one tenth the speed of light, or an energy of about five megaelectron volts. These are further slowed by a thin aluminum window and ultimately reduced to just a few electron volts of energy in a Penning trap. Successive bunches of antiprotons from the Antiproton Decelerator can be added to the trap, a process invented by TRAP called stacking. The ATHENA trap can hold its 10,000 antiprotons for many hours; ATRAP, with a better vacuum, has held half a million with no measurable losses for two months.

Nested Traps

THE TRAPPING of charged particles was pioneered decades ago, but the standard traps work only for particles that all have the same sign of electric charge (the same "polarity"). For example, a cylindrical Penning trap that holds positrons will not hold antiprotons. In this trap design, a magnetic field confines the particles radially and an electric field raises the potential at each end of the cylinder.

Matter Asymmetry in the Universe

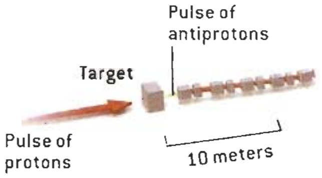
When the universe began in the big bang, the energy released should have produced equal amounts of matter and antimatter. How could such a universe evolve to what we see today, where almost everything is made of matter? The great Russian physicist Andrei Sakharov answered that question in 1967, when he showed that one of the necessary conditions for such evolution is a phenomenon called CP violation, which allows particles to decay at different rates than antiparticles.

Two experiments now under way—BaBar at the Stanford Linear Accelerator Center (SLAC) and Belle in Tsukuba, Japan—are studying CP violation in the decay of particles and antiparticles called B mesons. In August 2004 both announced direct observation of a large amount of CP violation by B mesons: a specific type of decay occurred much more often for the particles than for the antiparticles.

So far the amounts of CP violation observed mostly match the predictions of the Standard Model of particle physics. One particular reaction, however, does show a slight excess of CP violation. If confirmed, it would be a pointer to physics involving as yet undiscovered particles [see "The Dawn of Physics beyond the Standard Model," by Gordon Kane; SCIENTIFIC AMERICAN, June 2003]. The amount of violation observed so far, however, does not seem sufficient for Sakharov's model to account for the matter-antimatter asymmetry of our universe. ***—G.P.C.***

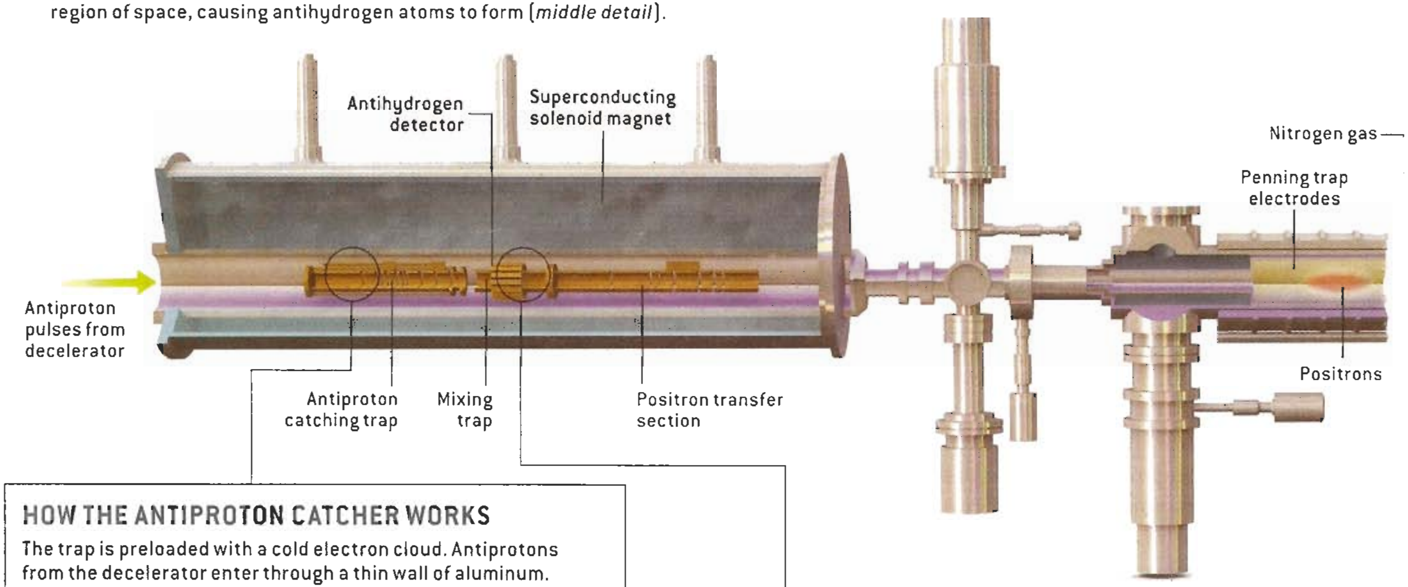
MAKING AND DETECTING COLD ANTIHYDROGEN

To make antihydrogen atoms, physicists must produce and bring together antiprotons and positrons. CERN's antiproton decelerator (*right*) supplies relatively low energy antiprotons to three experiments—ATRAP, ATHENA and ASACUSA. Magnetic and electric fields trap those antiprotons and positrons at each end of an evacuated, tubelike apparatus (*below*). The fields are then manipulated to bring the particles together in a mixing trap, where they form antihydrogen atoms, which are detected. The operating principles of the mixing trap were pioneered by the ATRAP group and its predecessor, TRAP. The diagrams below relate to the ATHENA apparatus.



ANTIPROTON CATCHER AND MIXING TRAP

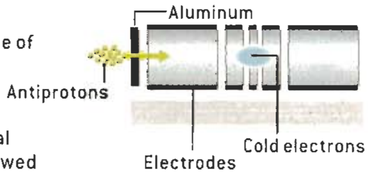
The antiproton catcher (*left*) collects pulses of antiprotons from the decelerator (*left detail*). When enough antiprotons have been accumulated, they are transferred to the mixing trap. That trap holds the antiprotons and positrons supplied by the positron accumulator shown at right in the same region of space, causing antihydrogen atoms to form (*middle detail*).



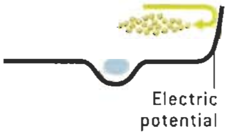
HOW THE ANTIPROTON CATCHER WORKS

The trap is preloaded with a cold electron cloud. Antiprotons from the decelerator enter through a thin wall of aluminum.

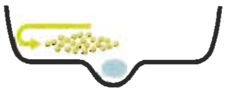
The aluminum slows some of the antiprotons



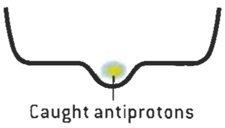
A high electrical-potential barrier reflects these slowed antiprotons back through the trap. High-energy antiprotons escape to the right



A high-potential barrier is quickly raised at the left-hand end, so the antiprotons bounce back and forth from end to end



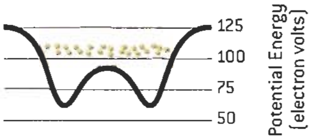
The antiprotons lose energy to the electrons on each pass and eventually settle in the trap center. The left barrier is lowered to let in the next pulse of antiprotons



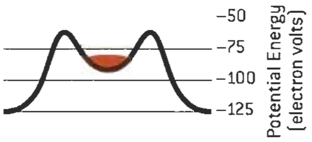
HOW THE NESTED MIXING TRAP WORKS

Positrons cannot be collected in the same potential well that gathers a cloud of antiprotons, so their trap must be nested within the antiproton trap.

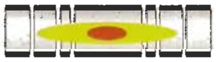
The antiprotons bounce back and forth in the confines of a large, deep potential well with a raised mound in the middle



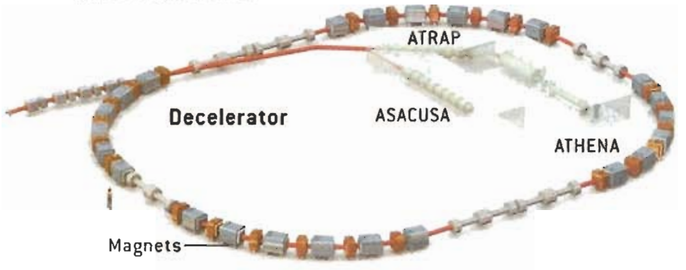
The positrons, having opposite charge, "see" the potential inverted, so the mound turns into a depression at the top of a broad hill



The depression traps the positrons within the same region of space as the antiprotons, enabling antihydrogen atoms to form

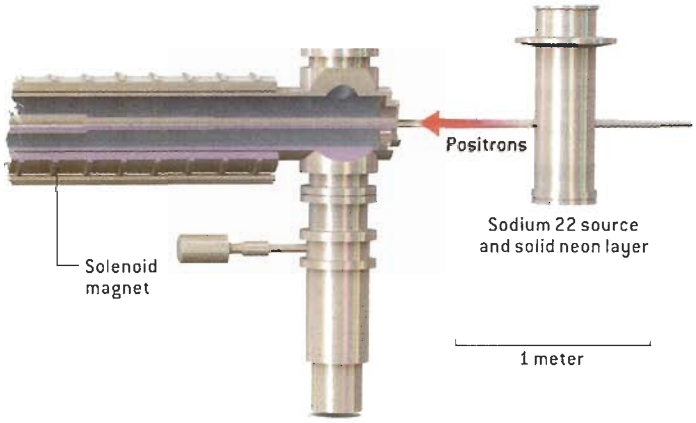


BIRD'S-EYE VIEW



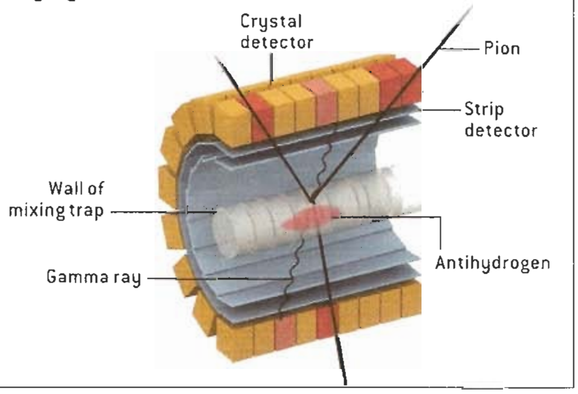
POSITRON ACCUMULATOR

Positrons emitted by a sodium 22 source (*far right*) are slowed first by passing through a thin layer of solid neon and then by collisions with nitrogen gas. A Penning trap captures the slowed positrons. When enough positrons have been accumulated, the nitrogen is pumped out and the positrons are transferred to the mixing trap.



HOW THE DETECTOR WORKS

When antihydrogen atoms form in the mixing trap, the antiatoms, being neutral, drift out of the trap and hit the walls of the container. There the antiproton and the positron are annihilated, producing three high-energy pions and a pair of gamma rays. Layers of particle detectors surrounding the mixing region detect these emissions.



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For the positrons, one can think of the end potential as a ramp and the particle as a ball rolling up the ramp. Positrons moving slowly enough are brought to a halt and turned around on the ramp, keeping them inside the trap. Unfortunately, antiprotons, with the opposite polarity, will see not upward-sloping ramps at each end but plummeting ones over which they will pour out, ultimately colliding with the material walls that maintain the vacuum of the trap and becoming lost. To trap antiprotons, one would have to reverse the electric field, thus inverting the potential.

The trick to trapping species of opposite polarity together was suggested in 1988 by Gabrielse and his co-workers: one puts a shallow trap for particles of one polarity inside a deeper trap for particles of the opposite polarity. The species trapped by the outer walls sees a deep well with a raised mound in the center, like the bottom of a wine bottle. The other species sees all the potentials inverted, and the mound becomes a mountaintop depression that holds them. Both ATRAP and ATHENA use a trap of this nested design to hold their antiprotons and positrons together; in the region of the mound, both particles coexist. Gabrielse and his colleagues demonstrated this scheme with protons and electrons in 1996 and with antiprotons and positrons in 2001.

Collisions among the jointly trapped particles occasionally result in a positron and an antiproton moving together along the same trajectory. These promptly end up orbiting one another, and, voilà, an antihydrogen atom is born.

Detection

HAVING MADE antihydrogen atoms, investigators face two problems: First, how do you detect the atoms, to prove that they are really there? Second, you have to do this quickly because the antihydrogen atoms, being electrically neutral, are held by neither of the two nested electromagnetic traps. The atoms fly rapidly out of the trap with whatever velocity they happened to have had when they were created.

The ATHENA collaboration uses this second problem as the solution to the first. When the departing atoms encounter the material walls of the container, they come to a halt. Almost immediately the positron gets annihilated by meeting an electron from an atom in the wall, and the antiproton gets annihilated in a nucleus. The first reaction typically generates two gamma rays of characteristic energy (511 keV) traveling in opposite directions; the latter creates two or three particles called pions. All those particles are relatively easy to detect. Whenever the detectors see the appropriate gamma rays and pions originating from the same place in the wall at the same time, the researchers know an antihydrogen atom was created and has now been destroyed.

Except it is not quite that simple. Some antiproton annihilations produce a shower of positrons, which in turn produce 511-keV gamma rays, two of which may be detected. Lone antiprotons can thus mimic the antihydrogen signal. The level of false signals has to be measured and deducted from the data.

The ATRAP group uses a markedly different technique that eliminates the background altogether. The team counts only the antihydrogen atoms that happen to travel along the axis of the cylindrical trap and happen to be weakly bound (all those traveling in other directions or in more tightly bound states escape undetected). These neutral antiatoms pass effortlessly through a high-potential barrier that blocks all stray antiprotons that are not part of an antiatom. Next the antiatoms encounter a strong electric field that strips apart the antiproton and positron of the weakly bound antiatoms. Finally, the newly naked antiprotons are captured in another electromagnetic trap. After a collection period, these antiprotons are released and detected by their annihilations on the nearby walls.

When positrons are absent from the nested trap, no antiprotons are detected, proving that lone antiprotons cannot surmount the potential barrier to get into the far trap. The count when the positrons *are* present is thus the count of neutral antihydrogen atoms that happened to be weakly bound and traveling in the right direction. No background has to be deducted.

In 2004, in a clever elaboration of this basic technique using an oscillating stripping field, ATRAP gathered information on how fast its antihydrogen atoms were moving—in other words, their temperature. The result was somewhat discouraging: the atoms produced and detected by the ATRAP collaboration have a temperature of 2,400 K, much higher than the 4.2 K of the liquid-helium-cooled trap components. To do detailed spectroscopy of antiatoms will require that they be well below 0.5 K, so that they can be collected in a neutral atom trap and studied by seeing how they absorb laser beams of various frequencies.

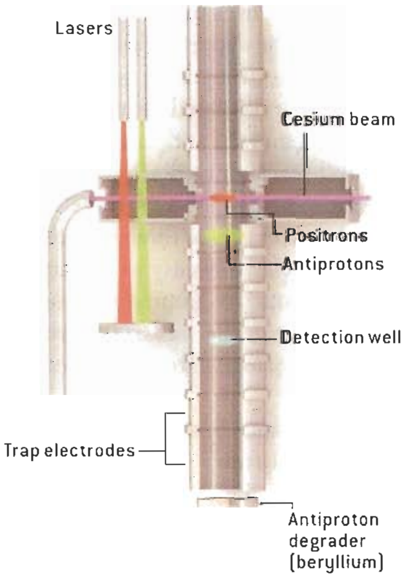
Laser-Controlled Production

IN AN EFFORT to create lower-temperature antiatoms, the ATRAP collaboration has developed a laser-controlled system for antihydrogen production. This system does away with the nested trap. Instead the positrons and antiprotons are held in adjoining but separate potential wells [*see box below*]. A chain of reactions, starting with a beam of laser-excited cesium atoms, transfers the positrons to the antiprotons to form antihydrogen. The chain of reactions is designed to transfer very little energy to the antiatom that is formed.

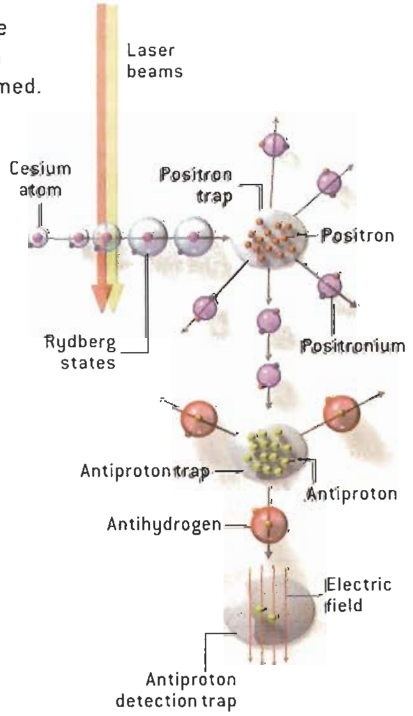
The ATRAP group carried out this experiment over the course of only a few hours at the very end of the experimental run in 2004, so they did not have time to optimize the method or to collect very many antiatoms. Indeed, they detected only 13 in total. Gabrielse explains that there is “good reason to believe that these atoms are far colder than the atoms produced in a nested Penning trap.” Many more are needed, however, to verify this hypothesis. Even then, a further step will be required before the antiatoms could be used for precision tests of CPT: the antiatoms are formed in bloated, highly excited states (called Rydberg states), and these will have to be

LASER-CONTROLLED PRODUCTION

The ATRAP collaboration has introduced a laser-controlled method of producing antihydrogen atoms without the need for nested traps [*device below; process below right*]. Instead the antiprotons and positrons are held in adjacent traps, and neutral positronium “atoms” [a co-orbiting electron and positron] transfer the positrons to the antiprotons. The sequence of reactions should ensure that the resulting antihydrogen atoms have low velocities [that is, a low temperature], but that has not yet been confirmed.



1. Cesium atoms from an oven pass through laser beams tuned to excite the atoms to bloated Rydberg states
2. Positrons in a trap capture the excited electrons from the cesium atoms, forming positronium, also in Rydberg states. Being neutral, the positroniums escape from the trap in all directions
3. Some of the positroniums travel to an antiproton trap where the antiprotons pick up the positrons, forming antihydrogen atoms, which escape from the trap in all directions
4. Some of the antihydrogen atoms travel to a second antiproton trap, where a high electric field strips off the positrons. The now trapped antiprotons are detected, proving the antihydrogen atoms were made



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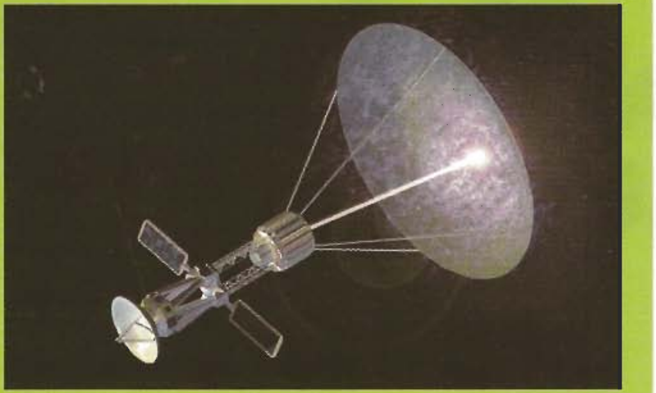
Antimatter Propulsion: What Would It Take?

According to NASA, 42 milligrams of antiprotons possess energy equal to the 750,000 kilograms of fuel and oxidizer stored in a space shuttle's external tank. The usefulness of such a concentrated source of energy for propulsion seems obvious, yet many difficult problems would need to be overcome before antimatter-powered space travel could become a reality.

The first requirement, of course, is a practical way to produce milligram quantities of antimatter. CERN's Antiproton Decelerator produces 20 million antiprotons every 100 seconds. If it ran 24/7 for a year, it would generate just 10 picograms of antiprotons.

Second, a way to store large quantities of antimatter is needed. Typical neutral atom traps hold only millions of atoms. In one scheme, proposed by Steven D. Howe and Gerald P. Jackson of Hbar Technologies at a NASA conference in 2003, antihydrogen ("$\bar{H}$" or "H-bar") would be stored in the form of solid pellets (hydrogen, and hence antihydrogen, freezes at 14 kelvins). The pellets, perhaps around 150 microns in diameter, would be electrically charged and suspended in an array of electrostatic traps.

Even given a significant store of antimatter, the energy of annihilation must be converted into thrust. When an electron and a positron annihilate, the energy is released as two gamma rays, which promptly fly off in opposite directions. Proton-antiproton annihilation produces short-lived particles called pions with high energy. These particles could be used to heat a tungsten core over which hydrogen was passed. The thermal expansion of the hydrogen would provide thrust.



PROPOSED ANTIMATTER PROPULSION system uses antimatter pellets to trigger fission explosions on a uranium-coated sail.

An engine that used magnetic fields to direct the pions themselves as the propellant would be far more efficient, but the total thrust would be much lower because of the tiny amount of propellant they would amount to.

Howe and Jackson proposed a third way using their antimatter pellets to power a sail system. The sail would be made of uranium-coated carbon, and the uranium would be induced to undergo nuclear fission when solid pellets of antihydrogen were fired into it. The ejection of debris from the fissions would propel the sail, which would pull along the spacecraft. That antimatter would induce the fission efficiently is entirely speculation at this point, however. *—G.P.C.*

"de-excited" before practical spectroscopy can be performed.

Also toward the end of 2004, the ATHENA group succeeded in compressing their antiprotons into a thin, dense column at the very center of their trap. Such a configuration may be very useful for future experiments involving magnetic traps (which will be needed to hold the antihydrogen atoms).

In other work, ATHENA members have examined properties of the antihydrogen production process. They have found that even when their positrons are at room temperature (300 K), almost as many antiatoms are produced as at ATHENA's usual 10 K operating temperature. That flies in the face of the simplest theories of how the antiatoms are formed, which predict thousands to millions of times fewer antihydrogens. Landua strongly believes that some additional mechanism is helping to stabilize the antihydrogen in the hotter plasma. (Gabrielse is highly skeptical of that conclusion.) If the process is actually reducing the antiatoms to their lowest energy state, as is desired for spectroscopy, that discovery would be good news for those wishing to test CPT symmetry.

Both researchers agree that producing antihydrogen atoms that are suitable for spectroscopy is the central challenge facing the groups now. Such antiatoms must have two properties: not only must they be cooler than 0.5 K, so that magnetic traps can hold them, they must also be in their ground state.

The Antiproton Decelerator usually runs from May to November every year, but it will not be run at all during 2005—CERN's accelerators have been shut down as a cost-cutting measure, following projected budget overruns from the Large Hadron Collider construction. The antiatom researchers will have to wait until May 2006 before they can resume their battle to beat hydrogen's evil twin into submission. SA

Graham P. Collins is a staff writer and editor.

MORE TO EXPLORE

Production and Detection of Cold Antihydrogen Atoms. M. Amoretti et al. in *Nature,* Vol. 419, pages 456–459; October 3, 2002.

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First Measurement of the Velocity of Slow Antihydrogen Atoms. G. Gabrielse et al. in *Physical Review Letters,* Vol. 93, No. 7, pages 073401-1–073401-4; August 13, 2004.

The ATHENA Web site is at **athena.web.cern.ch/athena/**

The ATRAP Web site is at **hussle.harvard.edu/~atrap/**

Additional information about antimatter and tests of CPT symmetry is online at **www.sciam.com/ontheweb**

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