Through the looking glass

CERN

Physicists are setting traps to catch antihydrogen, the simplest element in the mirror world of antimatter. Their results could challenge our picture of fundamental particles and forces, says Alexander Hellemans.

In a corner of one of the world's leading high-energy physics labs, a window on the antiworld is about to open. At CERN, the European Laboratory for Particle Physics near Geneva, some 150 physicists armed with sophisticated electrostatic traps, magnets and high-precision lasers aim to capture antiatoms and subject them to scientific interrogation for the first time. They hope to answer a simple, but fundamental, question: does antimatter behave differently from matter? If so, the theoretical underpinnings of modern physics would be shaken. "The result could be revolutionary," says Alan Kostelecky, a theorist at Indiana University in Bloomington.

Although antiatoms have so far eluded study, antimatter has been part of mainstream physics for more than 60 years. The British Nobel prizewinner Paul Dirac predicted the existence of positrons, the positively charged counterparts of electrons, in 1931. Soon after, they were detected in the shower of particles formed when cosmic rays hit the atmosphere, and physicists realized that every elementary particle should have an antimatter counterpart.

The Standard Model, which remains the best description of fundamental particles and forces that theorists can offer, predicts that matter and antimatter are exact 'mirror' images of one another. This means that antiatoms should have identical mass and spectra to atoms. If the experiments at CERN reveal that they do not, the Standard Model will be in trouble. But a small asymmetry between matter and antimatter could help solve another mystery: why our Universe is dominated by matter when, in theory, the Big Bang should have created equal amounts of matter and antimatter that would have annihilated one another.

Making subatomic antiparticles is easy: positrons are emitted in the radioactive decay of certain unstable isotopes; they can also be made by bombarding atomic targets with high-energy electrons. In the resulting collisions, some energy is converted to create electron–positron pairs. Likewise, high-energy protons can produce proton–antiproton pairs when they collide with neutrons or other protons. The hard part is bringing positrons and antiprotons together to form antihydrogen, the simplest antiatom.

Physicists had their first, fleeting glimpse of antihydrogen in 1995. At that time, CERN

A foot in both worlds

The first results from CERN's new Antiproton Decelerator are coming from a Japanese–European collaboration called ASACUSA, standing for Atomic Spectroscopy And Collisions Using Slow Antiprotons. "Asakusa is also the name of a district of Tokyo, so the acronym makes the Japanese connection evident," says John Eades of CERN, a member of the collaboration.

Instead of creating antihydrogen, the ASACUSA team is making 'antiprotonic' helium — a helium atom in which one electron is replaced by an antiproton. They are doing this by shooting antiprotons at a target of helium. "Technologically, this is the easiest and most efficient way to make an atom with an antiproton orbiting it," says Masaki Hori of the University of Tokyo, another team member.

Antiprotonic helium can exist at two energy levels, one of which annihilates one thousand times faster than the other, which survives for about 3 milliseconds. In the ASACUSA experiment, a laser pulse hits the helium target at the same time as the antiproton beam, and excites some of the antiprotonic helium atoms into the state in which they annihilate faster. "You can see a very sharp annihilation spike if your laser is tuned correctly," says Hori.

The frequency at which this spike occurs depends on the mass of the antiproton. The team has measured this mass to a precision of 0.5 parts per million[11]. "In the future we want to improve this precision to 5 parts per billion," says Hori. Any difference between the masses of protons and antiprotons would cause problems for the Standard Model.

operated a machine called the Low-Energy Antiproton Ring (LEAR). A German–Italian team, led by Walter Oelert of the Institute for Nuclear Physics Research in Jülich, fired a jet of xenon atoms across LEAR's antiproton beam, causing collisions that generated electron–positron pairs. Some of the positrons then combined with antiprotons to form antihydrogen. The researchers detected nine antiatoms[1], but these were travelling at 90% of the speed of light, and were observed by recording their annihilation in detectors made of silicon. This happened within 40 nanoseconds of the antiatoms' creation, making it impossible to perform measurements on them. "We could prove that antihydrogen exists," says Oelert. Similar experiments at Fermilab near Chicago in 1996 confirmed the finding, detecting several dozen antiatoms[2] — but the problem of capturing antihydrogen remained.

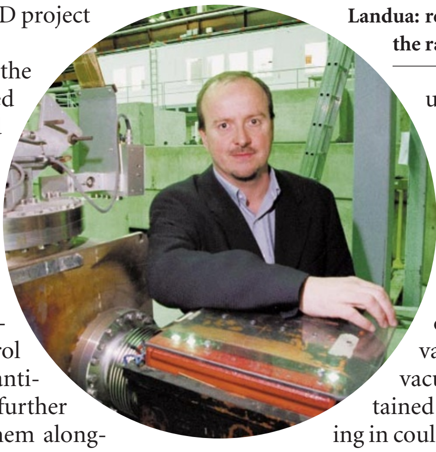
Applying the brakes

To move forward, physicists needed to slow antiprotons and positrons almost to a standstill, confine them using electric fields in devices called Penning traps[3], and then bring them together. By the mid-1990s, CERN had decided to close LEAR to free funding for the Large Hadron Collider (LHC), the lab's next enormous accelerator. In December 1996, a week before LEAR shut down, a team led by Gerald Gabrielse of Harvard University combined antiprotons and positrons in a single trap[4] — but did not succeed in forming any antiatoms. "Only a fuzzy-headed optimist would think you could do that in a week," says Gabrielse.

The enthusiasm generated by this experiment, combined with Japan's desire to keep working at the antimatter frontier, has ensured that a low-cost phoenix has risen from LEAR's ashes. In 1997, CERN's governing council approved construction of a new facility called the Antiproton Decelerator (AD). Japan supplied most of the SFr8 million (US$4.9 million) required; Germany, Italy, Denmark and Poland also contributed. The machine delivered its first antiprotons last December. Its running cost, paid from CERN's central budget, is SFr600,000 per year — a small price for a project that will give experimental activity a focus in the hiatus between the decommissioning later this year of CERN's existing centrepiece, the Large Electron–Positron collider, and the start of experiments at the LHC in 2005.

The new machine is much more streamlined than its predecessor. Antiprotons are generated at CERN by firing a beam of protons from an accelerator called the Proton Synchrotron at a target of iridium. Before entering LEAR, antiprotons were funnelled through three separate devices to slow them down. But they are fed directly into the AD, a storage ring with a circumference of 90 metres. "One machine does everything," says Stephan Maury, the AD project leader at CERN.

Once in the ring, the antiprotons are slowed by a technique called stochastic cooling. This relies on sensing the position of bunches of antiprotons and then sending a signal across the ring to apply microwave pulses to control their movement. The antiprotons are then further slowed by running them alongside a beam of low-energy, or 'cold', electrons. Operating on the same principle as a heat exchanger, this takes energy from the antiprotons. Finally, having been slowed from close to the speed of light to a tenth of that velocity, the antiprotons are delivered to the experimental apparatus.



Landua: relishing the competition in the race to study antihydrogen.

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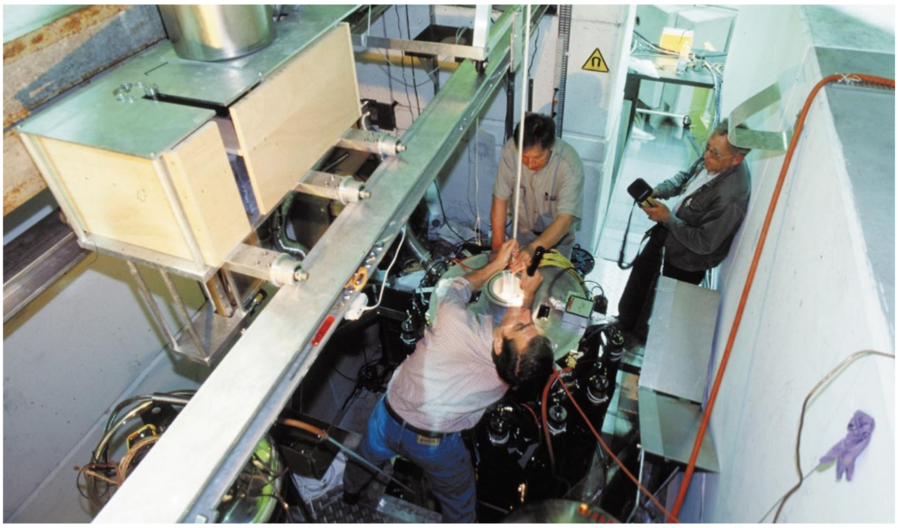
Come together

Two international collaborations, ATHENA, the Antihydrogen Apparatus, and ATRAP, or Antihydrogen Trap, will over the next few months try to combine positrons and antiprotons in their traps to create antihydrogen, which they will subject to high-precision laser spectroscopy. The positrons will come from the decay of radioactive sodium-22. Both teams have already begun capturing antiprotons. They are relishing the friendly rivalry. "If you don't have competition, you tend to become lazy and complacent," says ATHENA leader Rolf Landua, a physicist at CERN. A third team, the Japanese–European ASACUSA collaboration, is taking a different tack, aiming to create 'antiprotonic' atoms — atomic hybrids of matter and antimatter (see 'A foot in both worlds', opposite).

The ATHENA and ATRAP teams will first pass their antiprotons through thin aluminium foils. Many will be annihilated, but those antiprotons that survive will be slowed down sufficiently to allow them to be held in Penning traps. These contain electrodes that create electrical fields of varying strength. A high vacuum must be maintained inside, as atoms creeping in could annihilate the antiprotons. The ATHENA group plans to confine its positrons in a separate trap before attempting to combine the two[5], whereas the ATRAP team will feed both antiparticles straight into the same trap.

But antiprotons and positrons do not combine easily. The difficulty is getting positrons to shed sufficient energy to be captured by antiprotons. The ATHENA collaboration plans to shoot a bunch of antiprotons through a dense positron cloud in the hope that some will stick to form antihydrogen. Although few are expected to do so, the team believes it will produce enough antiatoms by using large traps.

The ATRAP researchers, meanwhile, will apply 'nested' electric fields to force the two types of antiparticle close together[6,7]. They will then use various techniques to coax them into combining[6]. One method, called three-body recombination, provides an extra positron to absorb energy from its companion. Another, called simulated emission, uses a laser to make positrons shed energy by emitting a photon of light. ATRAP will also use a new technique developed by Bart Noordam of the Institute for Atomic and Molecular Physics in Amsterdam, called pulsed-field recombination[8]. This uses an electric field to slow down positrons so that,



Hedging their bets: the ATRAP team has several strategies to combine antiprotons and positrons.

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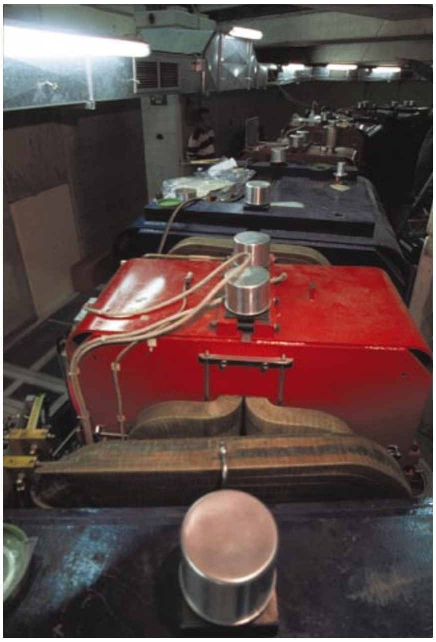
when the field is switched off, they can be captured by antiprotons. Finally, the ATRAP team will collide antiprotons with positronium — each 'atom' of which consists of an electron combined with a positron — in the hope of replacing some electrons with antiprotons[9]. "I'm being very careful not to put all our eggs in one basket," says Gabrielse, who leads ATRAP.

Both groups are cautious about predicting rapid progress. "This year I will be happy if we get back to where we were at LEAR," says Gabrielse. But with luck, he says, it may be possible to make small amounts of antihydrogen before the year is out.

Searching for asymmetry

Antihydrogen has no charge and so cannot be confined with electric fields. But antiatoms behave like tiny magnets, and the ATRAP team is already working on a magnetic trap. But this will only work if the antiatoms can be cooled to around 10 milliKelvin, by manipulating them with lasers or allowing the trapped antiatom cloud to expand. "We hope to produce lots of low-energy antihydrogen antiatoms, and then we can go ahead and construct a magnetic trap," says ATHENA's Landua. But if producing cool antihydrogen proves difficult, he says, it may be necessary to study beams of the antiatoms.

Either way, this is where the real physics will start. Both groups want to test a basic tenet of the Standard Model called CPT symmetry. This states that matter and antimatter should be exact opposites for three properties: charge (C), a spatial property called parity (P), and the direction of time (T). CPT symmetry means that atoms and their corresponding antiatoms should be indistinguishable by spectroscopy. By exciting antihydrogen with lasers tuned to specific wavelengths and detecting the light emitted in 'transitions', as positrons fall back from one energy level to another, physicists will determine whether the spectra of hydrogen and antihydrogen differ. If the spectra are different, the theorists will have some thinking to do.



All-in-one: the versatile Antiproton Decelerator.

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The ATRAP team plans to examine the transition from the 1*s* to the 2*s* energy state. This is difficult to detect directly, but can be studied through its interaction with another transition called Lyman α, or 1*s* to 2*p*. The Lyman α transition occurs at a wavelength of 121.56 nanometres. Atoms or antiatoms excited by Lyman α light return to their ground (1*s*) state after just 1.6 nanoseconds. As they do so, they emit photons, causing a detectable fluorescence. The Lyman α transition cannot itself be used to investigate the difference between atoms and antiatoms — because of its fleeting timescale, quantum effects mean that it occurs over a spread of wavelengths.

Atoms excited from 1*s* to the 2*s* state, however, stay there for 122 milliseconds before returning to 1*s*. This transition can be detected with great precision by illuminating a sample of antihydrogen or hydrogen with two lasers, one operating at the Lyman α wavelength, the other at around 243 nm. When most of the atoms or antiatoms in the sample are excited to 2*s* by this second laser, electrons or positrons are removed from the 1*s* level, blocking the Lyman α transition until they return to their ground state. This blocking causes a marked dip in the Lyman α fluorescence. So by tuning the precise wavelength of the 243-nm laser and determining when this dip occurs, it should be possible to measure the exact wavelength of the 1*s* to 2*s* transition.

Braking system: the Japanese–European ASACUSA team will use this device to slow down antiprotons.

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Until recently, physicists lacked a laser that could operate continuously at the Lyman α wavelength. But Theodor Hänsch and his team at the Max Planck Institute for Quantum Optics in Garching, Germany, have now developed one that can do the job[10].

The ATHENA team will exploit the fact that antihydrogen is easily detected when it annihilates. The researchers aim to excite trapped antiatoms with a laser beam so that they change their magnetic orientation. This will cause some antiatoms to be expelled from the trap, come into contact with matter, and annihilate. By tuning the laser, it should be possible to find the exact wavelength that causes maximal excitation. Again, if this wavelength differs between hydrogen and antihydrogen, it will violate CPT symmetry.

It may also be possible to investigate the influence of gravity on antihydrogen. According to the equivalence principle, part of the theory of general relativity, antimatter and matter should respond in the same way to a gravitational field. General relativity also predicts that the spectra of atoms should shift subtly if the gravitational field changes. The elliptical shape of Earth's orbit means that the gravitational pull we experience from the Sun shows tiny seasonal variations. If the spectra of hydrogen and antihydrogen respond differently to this variation, it will violate the equivalence principle.

It is this potential for major theoretical upsets that is enthralling physicists. It could even point the way towards the long-sought-after theory of quantum gravity. "If they find a difference between hydrogen and antihydrogen, it will provoke an explosion of work," enthuses Kostelecky. ■

Alexander Hellemans is a freelance writer in Naples.

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