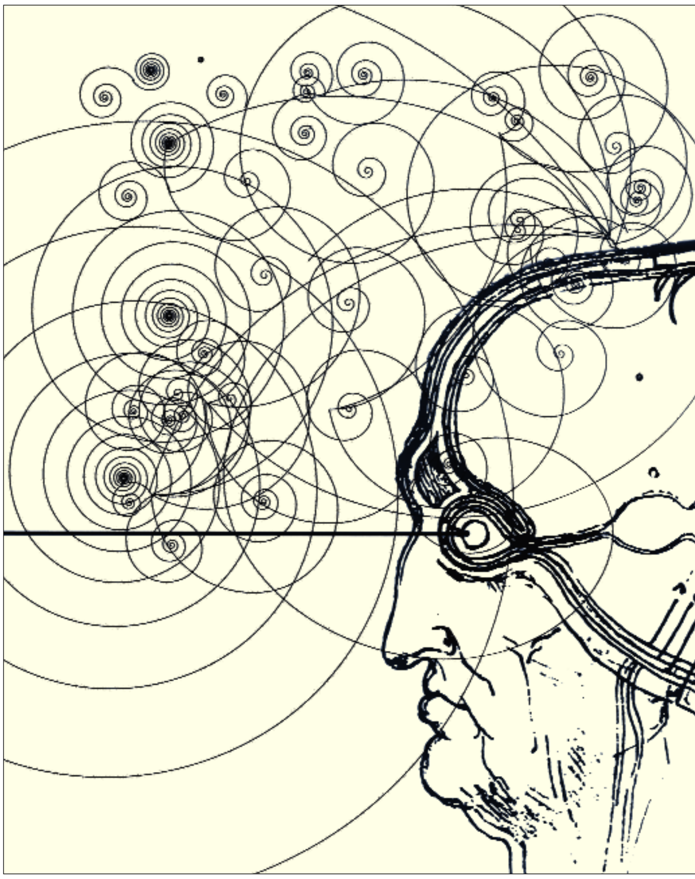
Probing the antiworld

One of the most staggering achievements in quantum physics was Paul Dirac's prediction of the anti-electron in 1930. By tirelessly modifying Schrödinger's description of the electron until it was consistent with special relativity, Dirac derived a beautiful equation that had additional "negative energy" solutions. He proposed that these solutions corresponded to a particle that has the same mass as the electron but the opposite electrical charge. Three years later the world's first antiparticle – called the positron – was discovered by Carl Anderson at the California Institute of Technology.

But Dirac's vision for antimatter did not stop there. By 1931 he had realized that the only other elementary particle known at that time – the proton – should also have a corresponding antiparticle: the antiproton. This particle was discovered at Berkeley in October 1955 (see box on page 32), setting the stage for the creation of atoms made entirely from antimatter.

A positron and an antiproton form the simplest type of anti-atom – antihydrogen. However, getting these two antiparticles to come together and form a single atomic system is no mean feat, not least because antimatter immediately annihilates when it comes into contact with ordinary matter. So why have physicists even bothered trying for the past 50 years?



Asymmetric world

When we look out at the universe from our vantage point here on Earth, one thing is clear: it is dominated by matter. Irrespective of how or where we look, antimatter simply does not exist in the quantities we would expect if matter and antimatter had been created in equal amounts in the Big Bang, as is generally assumed to have happened. Understanding this asymmetry between matter and antimatter is of enormous importance in physics and astronomy. After all, if every particle and antiparticle created in the Big Bang had annihilated with each other, there would be nothing out there to look at, and nobody down here to look at it.

One way to test the equivalence of matter and antimatter is to consider a fundamental quantum transformation known as the charge–parity–time (CPT) operation. When the CPT transformation is applied to a physical system, three things happen: every particle is converted to its antiparticle; each spatial co-ordinate is reflected so that left becomes right, up becomes down and forward becomes backward; and time is reversed. According to the CPT theorem, which lies at the heart of the Standard Model of particle physics, the universe is perfectly symmetric under this combined transformation, although certain combinations of C, P and T can be violated individually (see box on page 25).

There is currently no experimental evidence or even a compelling theoretical reason to doubt the validity of the CPT theorem. However, precision measurements of the properties of anti-atoms provide a unique way to test this once and for all. If CPT symmetry is violated, it could show up as a slight difference in the frequency of certain electronic or "positronic" transitions in hydrogen and antihydrogen atoms.

Synthetic antihydrogen

The prospect of creating antihydrogen in the laboratory was transformed from a distant dream into reality about 20 years ago. The catalyst was an improved way to generate dense, mono-energetic beams of antiparticles – a process known as "cooling". In particular, Simon van der Meer of CERN had invented a technique called stochastic cooling that enabled antiproton beams of very high quality to be produced and controlled. Indeed, it was this technique that led to the discovery of the W and Z particles in collisions between protons and antiprotons by Carlo Rubbia and the UA1 collaboration at CERN in 1983. Van der Meer and Rubbia shared the Nobel Prize for Physics the following year.

In the early 1990s, while most of us were busy figuring out how to get our positrons and antiprotons together, Charles Munger of the Stanford Linear Accelerator Center and co-workers at Fermilab, both in the US, hit upon a new approach to making antihydrogen. They

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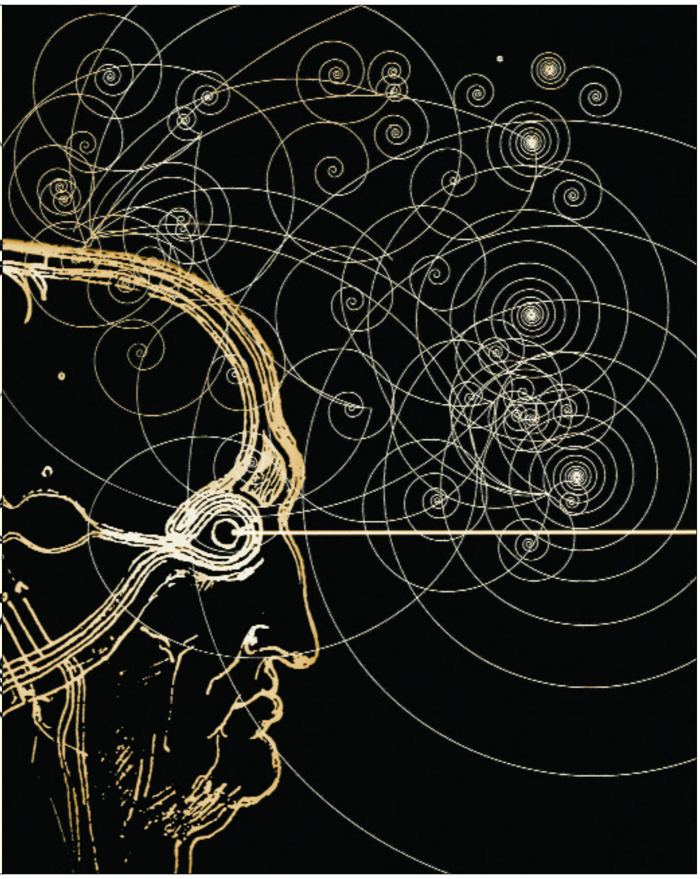
Half a century since the discovery of the antiproton, and more than 70 years since that of the positron, researchers at CERN can routinely produce millions of antihydrogen atoms. **Mike Charlton** and **Jeffrey Hangst** explain how these remarkable anti-atoms could be our best bet for understanding one of the most fundamental symmetries of nature



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realized that an antiproton travelling at relativistic speeds can create an electron–positron pair if it passes close to an atomic nucleus. And in a tiny fraction of these cases, the antiproton can bind with the positron and emerge as an antihydrogen atom. All that had to be done to observe these rare events was to circulate antiprotons as many times as possible in a storage ring.

This idea sparked a race between the two antiproton storage rings operating at the time: the "accumulator" at Fermilab and the Low-Energy Antiproton Ring (LEAR) at CERN. The race was won by the PS210 experiment at CERN, led by Walter Oelert and Mario Macri, which announced in 1995 that it had created 10 or so antihydrogen atoms. This result provided a media feast for CERN, but nonetheless proved to be the swan-song for LEAR. This unique facility finally closed at the end of 1996, by which time Munger and co-workers had produced about 100 antihydrogen atoms in the E862 experiment at Fermilab.

The news that LEAR was being closed down created a planning hiatus in the field, and the announcement was widely condemned (see *Physics World* December 1994 p3). But CERN's decision did have at least one positive outcome for those working on ultra-low-energy physics: it led to the formation of what were to become the two antihydrogen collaborations, ATHENA and ATRAP. A third collaboration called ASACUSA was also formed to study exotic hybrid atoms, such as antiprotonic helium, that contain both matter and antimatter (see "Antiprotonic helium" on page 29).

A number of individuals deserve credit for keeping this community together in a difficult period, and also for securing resources to develop a slimmed-down facility dedicated to physics with very low-energy antiprotons. In particular, the Japanese government provided important financial backing for a completely new, self-contained antiproton factory at CERN called the Antiproton Decelerator (AD). This machine, which was built from some of the leftovers from LEAR and the CERN antiproton source, produced its first beams of antiprotons in 1999.

Once news had filtered through that the AD was on the way, ATHENA and ATRAP researchers – including the present authors – began to gear up for the production of "cold" antihydrogen. The original antihydrogen atoms produced at CERN and Fermilab in the mid-1990s were very energetic or "hot", which meant they were poorly suited for precision tests of CPT.

The ultimate prize for the ATHENA team came in September 2002, when it reported that it had created the first cold antihydrogen atoms and directly observed their annihilation. ATRAP quickly followed with separate and quite distinct observations, and a new era in atomic physics was born.

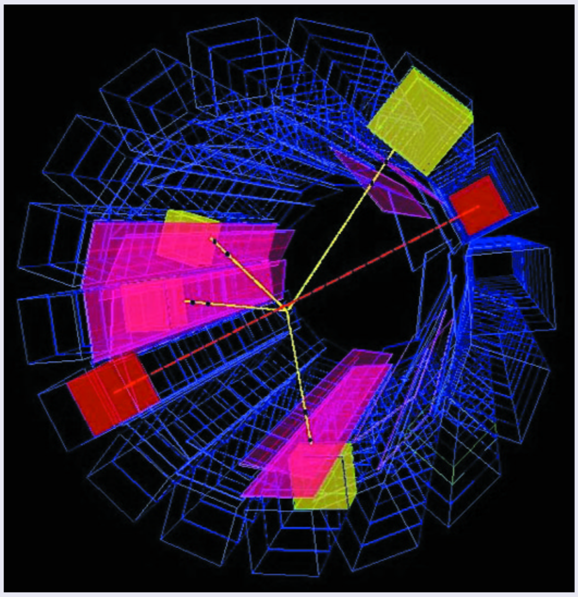
Experimental basics

The Antiproton Decelerator at CERN is tailor-made for producing antihydrogen. It consists of a storage ring with a circumference of 188 m into which the antiprotons – which have been generated elsewhere by firing high-energy protons into a stationary target – are injected. Once inside the ring, the antiprotons are decelerated in stages from an energy of 3 GeV to about 5.3 MeV using radio-frequency electric fields. The antiprotons also undergo stochastic and electron cooling to maintain the quality of the circulating beam. In

At a Glance: Antihydrogen

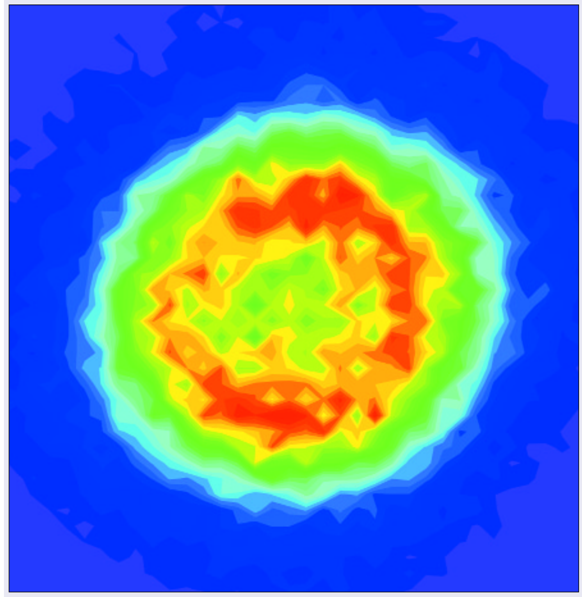
- Antihydrogen consists of a positron in orbit around an antiproton and was first produced at CERN towards the end of 1995
- According to the CPT theorem, antihydrogen should have the same atomic spectrum as hydrogen
- The challenge now is to trap antihydrogen atoms at cryogenic temperatures for long enough to allow precision tests of the CPT theorem
- Antimatter and matter annihilate instantly when they encounter one another
- It takes more energy to produce antimatter than is released when it annihilates, so, contrary to many science-fiction novels, antimatter will never be a viable energy source

1 Antimatter captured



This event display from the ATHENA experiment at CERN shows an antihydrogen atom that has annihilated after striking the wall of the Penning trap (centre, not shown). The nucleus of the anti-atom – the antiproton – annihilates into four charged pions (yellow tracks) that are detected with silicon microstrips (pink), while the positron annihilates into two back-to-back photons (red tracks) that are detected by caesium-iodide crystals (red cubes).

2 Cold antimatter



Nature

In 2002 ATHENA researchers produced the first cold atoms of antihydrogen, opening the possibility of comparing antihydrogen atoms with ordinary hydrogen. This image shows the transverse density of antiproton annihilation events integrated along the *z*-direction of a cylindrical Penning trap: red indicates high antiproton density; blue indicates low. The red ring corresponds to the inner wall of the Penning trap, which has a radius of 1.25 cm.

total, this cycle of events takes about 100 s, after which the AD ejects a focused burst of about 20–30 million antiprotons and prepares for the next injection.

Although distinctly cool by CERN's standards, 5.3 MeV corresponds to a temperature of about 60 billion kelvin, which is still way too high to produce cold antihydrogen. Fortunately, in 1986 Gerald Gabrielse of Harvard University and co-workers had developed a straightforward, if somewhat inefficient, technique for cooling antiprotons down to much lower temperatures.

First, the antiprotons are passed through a thin metal foil, where they are slowed via Coulomb interactions. Next, a fraction of the particles are captured in an electromagnetic "bottle" called a Penning trap, which confines them in the transverse direction using a strong solenoidal magnetic field and in the longitudinal direction using an electric field created by hollow cylindrical electrodes. Finally, the antiprotons undergo Coulomb interactions with electrons in the trap, which themselves are cooled by the emission of cyclotron radiation as they rotate in the magnetic field. This chain of events typically leaves about 10 000 usable antiprotons in the trap at a temperature of about 4 K.

Getting hold of the other component of antihydrogen – positrons – is somewhat easier, partly because they can be continuously produced by the million from radioactive sources. The ATHENA experiment accumulates positrons using a technique pioneered by Cliff Surko and colleagues at the University of California in San Diego. Here, positrons are slowed via collisions with nitrogen gas, accumulated for about 200 s in a Penning trap, and finally transferred to a second Penning trap in the same magnet used to trap the antiprotons. All one has to do to produce antihydrogen is release the antiprotons into this positron plasma, where roughly 15% of the trapped antiprotons end up as the nuclei of antihydrogen atoms.

Irrespective of how or where we look, antimatter simply does not exist in the quantities we would expect

When an antihydrogen atom forms, it has no net charge and is therefore not confined by the electromagnetic fields in the Penning trap. Once it escapes from the apparatus, the anti-atom can be detected in two ways. The method favoured by ATHENA is to record the annihilation of anti-atoms when they come into contact with the trap electrodes, which produces a "flash" of pions and gamma rays that can be detected with a sophisticated imaging detector (figures 1 and 2). ATRAP, on the other hand, uses electric fields to pull weakly bound anti-atoms apart, and then traps and records the antiprotons as they annihilate. In both cases the antimatter signals are unambiguous, allowing researchers to study the way anti-atoms form and to begin exploring their properties.

Cryogenic gymnastics

Since hydrogen is the most abundant element in the universe, you might think that the process by which a proton and electron combine to make an atom – or the equivalent "antiprocess" – is fairly straightforward. If that was the case, however, many of us could have packed up and moved on to other experiments some time ago! The difficulty arises because antihydrogen atoms need to be produced at liquid-helium temperatures before we can study them in any detail.

At these cryogenic temperatures antihydrogen can form via two different reactions: "radiative capture", whereby an antiproton captures a passing positron and releases the excess energy as a photon; or the "three-body" process whereby an antiproton interacts with two positrons, one of which acts as a spectator that removes the excess energy and leaves an antihydrogen atom behind.

Provided that the antiprotons and positrons are in thermal equilibrium, the rate of these reactions depends on the temperature of the positron plasma: the rate of radiative capture is inversely proportional to the square root of the positron temperature, T, while the rate of the three-body process scales as $T^{-9/2}$. This makes the three-body reaction the dominant mechanism for antihydrogen production at liquid-helium temperatures.

Each reaction also tends to produce antihydrogen atoms with different binding energies and hence different principal quantum numbers, n. These quantum numbers are the same as those that apply to ordinary hydrogen, only here they describe the energy level occupied by a positron rather than an electron. The radiative reaction favours tightly bound anti-atoms with $n \sim 1-10$, while the three-body process produces highly excited antihydrogen with $n > 40$.

In practice, both reactions produce a distribution of atomic states rather than atoms with a single, well-defined principal quantum number. Furthermore, the internal structures of these states can be greatly affected by the strong magnetic field in the Penning trap and by collisions in the positron plasma. Producing useful antihydrogen is therefore a considerable experimental challenge – especially if the antihydrogen detector has to be in close proximity to the cryogenic traps, as it was in ATHENA.

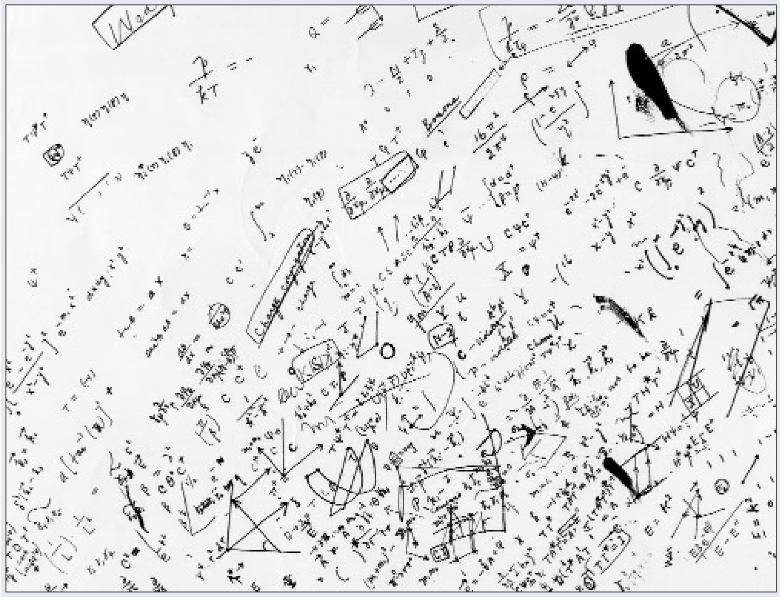
Trapping antimatter

In the last few years the ATHENA and ATRAP experiments have produced many millions of cold antihydrogen atoms. But in order to make precision tests of CPT and, perhaps, to measure how antimatter behaves under gravity, we need to somehow confine these atoms in a purely magnetic trap (figure 3). Such traps are shallow – they are typically only able to trap atoms that have temperatures less than 1 K – so if antihydrogen is to be trapped at all, it should be produced at a similar temperature. Furthermore, it should preferably be in its ground state, which means we need to know the kinetic energies and the principal quantum numbers of the antihydrogen atoms.

The different antihydrogen detection schemes adopted by ATHENA and ATRAP provide complementary information. ATHENA's annihilation method, for instance, allows us to detect all the antihydrogen atoms that survive the harsh environment of the positron plasma, independent of their binding energies or velocities. The field-ionization technique adopted by ATRAP, however, is restricted to high-n states due to limitations on the voltages that can be applied to the electrodes in the Penning trap. Moreover, this method is only sensitive to antihydrogen atoms emitted along the axis of the trap (coincidentally, this is precisely the region of solid angle *not* covered by the ATHENA detector).

Towards the end of 2003 the ATHENA collaboration figured out that most of the antiproton annihilations it observed were caused by antihydrogen, as opposed to losses of antiprotons from the trap. Once we applied a simple method to remove events that we knew did

The CPT theorem



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Prize-winning scribbles In 1956 Tsung-Dao Lee, along with Chen Ning Yang, showed that parity is not conserved in weak interactions. This discovery won them the 1957 Nobel Prize for Physics.

What would happen to the universe if we could change each and every particle into its associated antiparticle, reverse all three directions in space, and force time to run backwards? The answer, according to the CPT theorem, is nothing – we would find ourselves in a universe that behaves exactly as the original one. But how can we be sure?

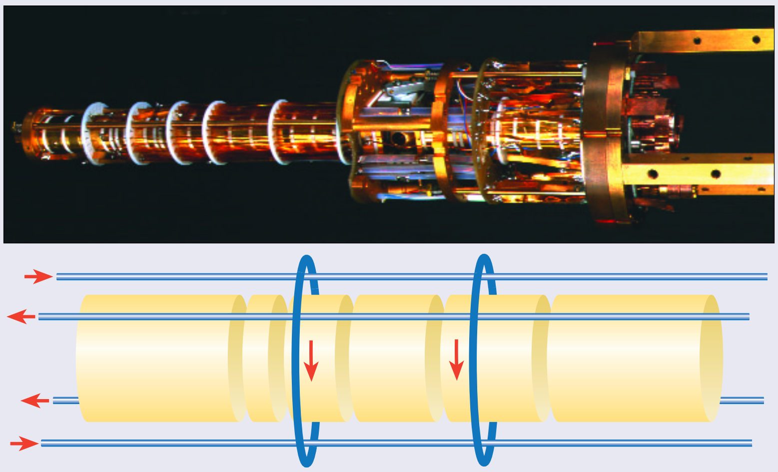
At various times in the past 100 years physicists have thought that each of the three discrete symmetries – charge conjugation, denoted by C; parity reversal or P; and time reversal or T – is respected by nature. In 1956, however, Chen Ning Yang and Tsung-Dao Lee realized that the weak interaction (which is responsible for radioactive decay) does not conserve parity – a prediction that was soon confirmed in experiments led by Chien-Shiung Wu and co-workers. Then, in 1964, James Christenson, James Cronin, Val Fitch and Rene Turlay discovered that CP symmetry was violated in the decay of neutral K-mesons. Indeed, it is now thought that the breaking of CP symmetry may help to explain why the universe is dominated by matter (see *Physics World* July 2003 pp27–31). It is therefore natural to turn our attention to CPT: could this bedrock of modern quantum field theory, which underpins the Standard Model of particle physics, also be violated?

Now, apart from marvelling that physicists actually get paid to ask such a question, you are probably wondering what all of this has to do with antihydrogen. The point is that the CPT theorem is just that – a theorem that needs to be put to the test. And when it comes to precise experimental tests, the hydrogen atom is something we understand very, very well. The CPT theorem demands that hydrogen and antihydrogen have the same spectrum. And since the frequency of a particular transition in the hydrogen atom called the 1s–2s line has been measured absolutely to a precision of about one part in 10^{15}, the holy grail of anti-atom research is to make a similarly precise measurement with antihydrogen atoms.

The current best test of CPT violation involves measuring the mass difference between neutral kaons and their antiparticles in experiments, which have shown that any difference must be less than 10^{-18} times the kaon mass. Fractional quantities like these should, however, be taken with a pinch of salt because we do not have a strong candidate mechanism for CPT violation. In other words, we do not know if the degree of CPT violation – if CPT is indeed violated – is proportional to mass or frequency or to some other quantity.

Antihydrogen provides a unique opportunity to accurately compare baryonic matter – i.e. matter made of particles such as protons and neutrons – with its antimatter counterpart in a very straightforward experiment. Our best measurement of this, performed by Gabrielse and co-workers, involves the charge-to-mass ratio of protons and antiprotons, which agree to one part in 10^{10}.

3 Trapping antimatter



Charged antiparticles such as positrons and antiprotons can be trapped easily using Penning traps, such as this one from the ATRAP experiment (top). Antihydrogen atoms, on the other hand, are neutral and therefore escape the trap and annihilate with ordinary matter. To confine anti-atoms, we need to surround the Penning trap electrodes (yellow in both figures) with additional magnetic fields, which act on the dipole moments of the atoms and cause those in certain states to seek the field minimum at the trap centre. The necessary field configuration can be obtained by adding a transverse multipole winding (quadrupole shown) and longitudinal "mirror" coils around the Penning trap (arrows denote the direction of current in the coils). The challenge is to do this without disturbing the confinement of the charged antiprotons and positrons.

not result from antihydrogen, we suddenly realized that millions more anti-atoms had actually been synthesized! Indeed, when the experiment was running smoothly, some 400–500 antihydrogen atoms were being produced each second.

One of the most distinctive aspects of antihydrogen production is its predicted temperature dependence due to the radiative-capture and three-body reactions. However, when ATHENA researchers decided to investigate this in 2003, by varying the temperature of the positron plasma between 15 and 3500 K using a radio-frequency signal, they were faced with several surprises. At cryogenic temperatures, for instance, they did not see the expected increase in antihydrogen production when the three-body process was supposed to have kicked in. At room temperatures and above, on the other hand, the observed temperature dependence was more consistent with the radiative reaction. However, the measured rate was at least an order of magnitude too high to be explained by this process.

These results are still not fully understood, but Francis Robicheaux of the University of Auburn has recently pointed out that the three-body process really involves a complex sequence of capture and release. Since the antiprotons in both ATHENA and ATRAP move rapidly in and out of the positron plasma, the reaction could therefore be arrested. Another possibility, which resulted from a careful analysis of the directions in which the antihydrogen atoms were emitted from the ATHENA apparatus, is that the antihydrogen atoms are produced before the antiprotons can come into equilibrium with the cold positrons. In this case, the temperature dependencies described earlier do not apply. Furthermore, the ATRAP collaboration had also measured antihydrogen temperatures well above the 4 K environment of its apparatus.

In 2002 the ATRAP collaboration used its field-ionization technique to determine the binding energies of antihydrogen states. The Coulomb field between the positron and antiproton in a ground-state antihydrogen atom is a colossal $5\times10^{9}\,\mathrm{V\,cm^{-1}}$, which means that we would need an electric field of at least this strength in order to separate the pair.

However, it is easy to show, using the Bohr model, that the Coulomb force diminishes rapidly as the fourth power of the principal quantum number, n. This means that antihydrogen atoms with n greater than about 40 can be separated into their constituents by letting them drift across a weaker electric field. Using this technique, the ATRAP team found that its antihydrogen states correspond to principal quantum numbers in the range $n = 40$–70, which means the antihydrogen is likely to have been formed via the three-body process.

There is currently no experimental evidence or even a compelling theoretical reason to doubt the CPT theorem

Antimatter to order

The basic ATHENA and ATRAP formation schemes produce antihydrogen atoms with a range of different quantum states, but ideally we would like to have more control over this outcome. One way to do this is to use lasers, which should enable us to produce antihydrogen atoms with a particular principal quantum number or binding energy.

In 2004 the ATHENA collaboration attempted to stimulate the radiative process by which an antiproton and a positron combine. Using an intense carbon-dioxide laser with a carefully tuned wavelength to cross the Penning trap with infrared radiation during the positron–antiproton mixing stage, we hoped that we could produce antihydrogen states with a principal quantum number of $n = 11$. Unfortunately, we did not see any enhancement in the rate of antihydrogen production, and further study is needed to determine whether or not this method is feasible.

Another way to produce antihydrogen atoms with particular quantum numbers is to force antiprotons to interact with "positronium" atoms – bound states of an electron and a positron. This approach was first suggested by Bernie Deutch of the University of Aarhus in 1986, but soon afterwards one of us (MC) realized that the reaction rate would be enhanced dramatically if highly excited states of positronium could be used. Moreover, by selecting the quantum state of the positronium we would be able to tell in advance which state the resulting antihydrogen atom would be in.

In 1998 Eric Hessels and colleagues at the University of Toronto came up with an ingenious way to implement

CERN

Accumulating anti-atoms
Antiprotons entering the ATHENA experiment from the AD (left, not shown) are stored in a superconducting magnet, where they are joined by positrons from the positron accumulator (right).

this scheme called double charge exchange. First, caesium atoms, which have been prepared in $n \sim 50$ states with a laser, are allowed to interact with a cloud of cold positrons. A positron then captures the excited electron from a caesium atom via charge exchange to form positronium. Finally, a second charge-exchange reaction between positronium and nearby antiprotons leads to the formation of an antihydrogen atom with $n \sim 45$.

Earlier this year the ATRAP collaboration observed this sequence of reactions. In a proof-of-principle experiment, the team detected about 14 antihydrogen atoms when lasers were tuned to produce caesium atoms in the $n = 37$ state (see *Physics World* March pp24–25). Crucially, the team did not observe any events when the lasers were detuned or when positrons were absent. However, the next challenge is to determine the kinetic energies of the anti-atoms produced in order to determine whether this approach can produce very cold antihydrogen.

The antimatter spectrum

We have only just crossed the threshold into the domain of cold antimatter research and caught our first glimpses of the science within. But already we are confronted by puzzles and promise in equal amounts.

As described earlier, both the ATRAP and ATHENA experiments indicate that the antihydrogen produced by simply mixing antiprotons and positrons is warmer than the ambient temperature of a few degrees above zero. It thus remains to be seen if these relatively simple and highly efficient production techniques are compatible with state-of-the-art magnetic traps, which would allow us to study the properties of anti-atoms. New processes and techniques, such as the Deutch positronium method, may be needed, but it is our belief that the first experiments on the spectrum of antihydrogen will be possible in the next few years.

ATHENA's work is now complete, but a new collaboration led by one of us (JSH) called ALPHA (Antihydrogen Laser PHysics Apparatus) will now concentrate on trapping antihydrogen atoms. In ATHENA the antihydrogen atoms annihilated a few microseconds after they were formed, but the ALPHA team hopes to trap them for many seconds or longer. Only then will it be possible to perform precision spectroscopic tests of CPT invariance.

Finally, it should be noted that none of this effort to probe the structure of anti-atoms will be possible without CERN's AD. In an ominous recent shift in mood, reminiscent of that surrounding the ill-fated LEAR in the 1990s, CERN management is once again looking at its low-energy antiproton research from a financial point of view. Indeed, the AD will not operate at all this year, and the amount of beam-time allocated to the machine in 2006 has been slashed because the Large Hadron Collider is over budget.

Let us hope that this time, good sense will prevail and low-energy antimatter research will continue to flourish. After all, this field has done so much recently to keep CERN and particle physics in the public eye.

More about: Antihydrogen

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