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Antihydrogen on tap

Michael Charlton

Department of Physics, University of Wales Swansea, Singleton Park, Swansea SA2 8PP, UK

E-mail: M.Charlton@swansea.ac.uk

Abstract

Plentiful quantities of antihydrogen, the bound state system of the antiparticles the positron and the antiproton, have recently been made under very controlled conditions in experiments at the European Laboratory of Particle Physics (CERN) near Geneva. In this article I describe how that was done, and why.

Preamble

> *Positrons and antiprotons are now routinely made and stored for use in collider experiments.*

The above is quoted from the *Advancing Physics A2* textbook [1][1]. We hope that this article will convince you that the next few sentences in a future edition should describe how they are also routinely manipulated and used to create atomic antimatter.

It's a challenging experiment—so why bother?

Bringing together the two antiparticles, the positron and the antiproton, to form antihydrogen is a formidable experimental challenge and one that was not undertaken lightly. For a start, the antiparticles annihilate readily on contact with matter, so they must be stored for use in high vacuum conditions. Moreover, both species are produced (from β^+-decay for positrons and as a result of high energy proton–proton collisions for antiprotons) with kinetic energies much too high to allow them to become bound. Thus, sophisticated techniques and apparatus to cool and handle them must be developed. So, we must provide an answer to the question: "why is it so important to pursue this difficult goal".

[1] This is from a UK course with this book aimed at 17–18 year-olds.

For a few decades now it has become apparent to physicists that fundamental asymmetries are hidden deep within nature. For example, in the 1950s it was discovered that the weak nuclear interaction (which is responsible for β-decay) violates parity conservation. (Parity conservation means that left and right and up and down are indistinguishable in the sense that an atomic nucleus throws off decay products up as often as down, and left as often as right [2].) Specifically, β^--decay involves the emission of an antineutrino that always spins in a left-handed corkscrew fashion. Conversely, β^+-decay only produces neutrinos that are right-handed. However, the defective parity 'mirror' can be mostly repaired by adding so-called charge conjugation, which, loosely speaking, means that interactions are unaffected when every particle is substituted by its antiparticle. For a while it was believed that the laws of nature would obey the combination of parity reversal and charge conjugation. But by the mid-1960s this was found to be untrue for a small class of reactions involving unusual, fleeting particles called K-mesons. Since then it has been assumed, and there is some experimental evidence to support this, that the small blemish in the combined charge conjugation/parity reversal 'mirror' can be corrected by the application of time-reversal.

However, this sort of three-way switch involving charge, parity and time differs from the three discrete symmetries, or any two-way combination of them. The charge/parity/time combination exists as a theorem that can be proved using the basic postulates of quantum field theory. Such theories are the cornerstone of our current understanding of the universe, but are widely recognized as being incomplete. So testing this unique three-way switch is going to the heart of our understanding of nature.

Just why this is so pertinent is as follows. Our current picture of the beginning of the universe involves the so-called Big Bang, which is thought to have been an energetic event that created equal amounts of matter and antimatter. Why then did they not all annihilate one another and leave a universe devoid of matter—a universe with no stars or planets, and no prospects for life? Searches for large amounts of remnant antimatter (e.g. via signatures of galaxy–anti-galaxy annihilation) in the universe, have failed to find any trace. Though investigations continue, with ever increasing sensitivity, we can currently say that our universe seems to be matter dominant, in other words asymmetric. The other fact to add to this potent brew is that the amount of asymmetry we can currently identify via numerous studies of fleeting and rare particles isn't enough to explain the existence of the material universe.

So the bottom line is this: we don't really understand the evolution of the universe and why there is anything much out there, or down here, at all. This makes testing the symmetries of nature of paramount importance. We don't have anything much to go on from theory (thought there is a resurgent interest in this area), so, experimentally, we have to look where and when we can. The creation of cold antihydrogen in amounts suitable for study has opened a new door on symmetry, hopefully one that will be amenable to precision laser spectroscopic comparisons with the spectral lines of hydrogen. We will discuss this further in the final section of the article.

The other major area where modern physics needs input from experiment is gravity. In 2005, the International Year of Physics, or Einstein Year as it is known in the UK, it is appropriate to recall that Einstein spent many of the latter years of his life searching for a unified theory of the forces of nature based upon his own success in describing gravitation. We now know that, although the unification ambition was sound, the methodology was not. Indeed it has turned out that gravity still eludes a satisfactory unified description (with electromagnetism and the weak and strong nuclear forces). Any new test of gravity (usually referred to as tests of the Weak Equivalence Principle) can offer new information and potential pointers towards a consistent theory of quantum gravity. Currently we do not have a theory that unites quantum mechanics with gravitation. Like an unfinished story, at the moment we have a *quantum* theory that works on a microscopic level (e.g. particles, atoms and molecules) and a *classical* theory that works on the macroscopic scale of the universe.

So where does antihydrogen fit in? Well, to date, we have absolutely no information on the gravitational interaction of antimatter. If we invoke our earlier three-way switch of charge, parity and time reversal, all we can say is that an antiatom will fall to an anti-Earth with the same acceleration as an atom falls to Earth! A moment's thought will show the logic of this: our three-way switch not only throws the falling particle, but also the object it is falling towards. (It becomes an anti-Earth!) Thus, our notions of symmetry can say nothing about the antiparticle falling towards Earth. Gravitational experiments on individual (or even small collections of) antihydrogen atoms will not be easy, but the potential pay-off is high. It is an experimental area crying out for investigation. We will return to this in our concluding section too.

The experiment

In 2002, two groups working at CERN, which has unique facilities for producing low energy antiprotons, announced that they succeeded in producing cold antihydrogen [3,4]. The author is a member of one of these groups, the ATHENA collaboration, and as such the remainder of this article will be mainly based upon the methodology and findings of that team. A detailed review of the achievements of the ATRAP collaboration can be found elsewhere [5].

Antiprotons

What does CERN have to offer that can't be found elsewhere? Accelerator physicists at CERN have always been proud of the diverse capabilities of the machines they have built and the techniques they have pioneered in order to run these instruments up to and beyond design specifications. One important difference between CERN and all other particle physics laboratories is that, early on, they realized the physics benefits that would accrue from decelerating antiprotons so that experiments could be performed at low energies, with the antiprotons stopped in a small volume.

Why is deceleration necessary? In order to form antiprotons in the first place one must supply energy in the form of energetic bursts of protons (about 10^{13} per burst at kinetic energies over 20 GeV), and collide these with a fixed target—also a source of protons, but now stationary. It is another application of the famous equation $E = mc^2$; the more 'E' you put in the more 'm' you can create. The antiproton production reaction goes something like:

$$\text{proton} + \text{proton} \rightarrow 3 \text{ protons} + \text{antiproton}.$$

A slice of the antiprotons thus produced is creamed off into a storage ring (by this time we have about 10 million of them) where it is held by appropriate electric and magnetic fields in a high vacuum environment (to avoid annihilation). Here, the antiprotons are, to begin with, whizzing round with speeds close to that of light, and much too high to be useful for controlled antihydrogen formation. This is where the deceleration comes in. Over the next minute and a half the antiprotons are slowed within the storage ring, which is the appropriately named Antiproton Decelerator (or AD for short). Deceleration must be accompanied by a process known as cooling (we describe an example below), to prevent defocusing of the circulating antiprotons. Once this is done the antiprotons are ready for ejection from the AD at a modest kinetic energy (by CERN's standards) of 5 MeV. (The corresponding antiproton speed is about 3×10^7 m s^{-1}.) They are delivered to the experiment in a convenient 200 ns burst.

Despite the heroic deceleration already achieved, the antiprotons are still far too energetic. The final stage of slowing down is, however, relatively crude. On entrance to the ATHENA experiment the antiprotons pass through an aluminium foil whose thickness is carefully optimized such that half of them emerge from the far side into an awaiting trap. The other half stop in the foil. Under these circumstances the chances of having very low energy antiprotons (here with kinetic energy below 5 keV) are maximized. The ATHENA trap is a so-called Penning trap and utilizes a strong magnetic field (3 T) along the axis of the instrument to radially confine the antiprotons, and an electric field formed by the voltages applied to a set of cylindrical metal electrodes to provide axial confinement. A schematic illustration is given in figure 1(a).

The antiprotons in the burst with kinetic energies less than 5 keV (by now we have unfortunately lost most of them, with just 10^4 remaining) are reflected by the end electrode of the trap (figure 1(b)), and before they can return to the foil the latter is rapidly raised to -5 kV and the antiprotons are captured (figure 1(c)). If this were all that was going on then the antiprotons would pass back and forth along the length of the catching trap for long periods. However, before their arrival we have taken care to provide them with a means to slow down further. Nestling in a central region of the Penning trap is a cloud of about 10^8–10^9 electrons. In the strong magnetic field these light particles lose kinetic energy as synchrotron radiation and quickly reach thermal equilibrium with their surroundings. In this case it is the metal electrodes of the trap, which are held at a temperature of 15 K. The antiprotons pass repeatedly through this cloud, to which they are efficiently coupled via the Coulomb interaction. The net result is that they lose kinetic energy to the electrons (which in turn self-cool in the strong field). After 10–20 seconds the antiprotons end up cohabiting with the electrons in the inner trap (figure 1(d)). The latter can be easily removed by short, sharp voltage 'pips' to leave a pure antiproton ensemble at 15 K, where now their speed is only around 500 m s^{-1}. The antiprotons are now ready.

Positrons

Whilst this has been going on another section of the ATHENA apparatus has been busy accumulating positrons. The latter are the most readily accessible antiparticles and are emitted in nuclear β^+-decay. Conveniently, radioactive sources are commercially available and one of the most commonly used isotopes is ^{22}Na. The sodium in common salt, and the only stable isotope of sodium, is ^{23}Na, which has 12 neutrons to go with the 11 protons in its nucleus. ^{22}Na on the other hand has one less neutron, and is missing a little

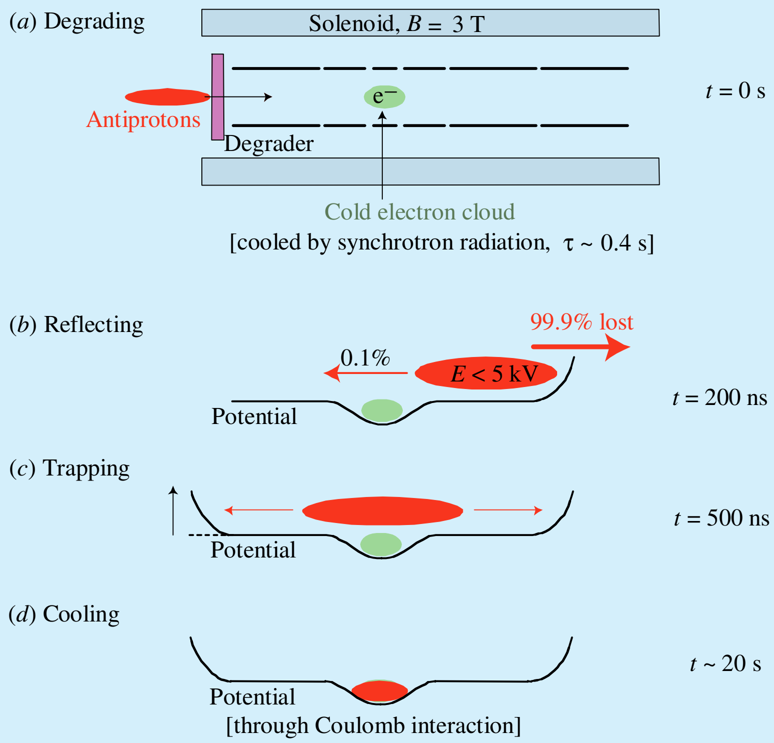

Figure 1. (*a*)–(*d*) Schematic illustration of antiproton capture and cooling in a Penning trap. The metal electrodes, shown in section, are arranged along the axis of the solenoid. See text for details. Note that the polarity of the potentials is negative in (*b*)–(*d*).

of the nuclear glue. Thus, it decays by emitting a positively charged particle, the positron, with a half-life of about $2\frac{1}{2}$ years. The reaction can be summarized as

$$^{22}\text{Na} \rightarrow {}^{22}\text{Ne} + \text{positron} + \text{neutrino}.$$

The sealed radioactive source is held in a vacuum enclosure and cooled to a temperature of a few kelvin. The reason for this is that the source is coated with a thin (about 1 μm) layer of neon, which will only condense onto materials held at very low temperatures. This thin neon layer performs a similar task to the aluminium foil that helped to slow down the antiprotons. The need to slow down the β^+-particles arises due to their high kinetic energy and energy spread on emission from the source.

The positrons slow down in the film, and many stop there before they annihilate with an atomic electron. It turns out that atomic scattering (whose cross section scale is typically set by the size of the atoms, or around 10^{-10} m) is much more likely than annihilation when positrons collide with atoms. The annihilation cross section, which is essentially a measure of the probability of the disappearance of a positron–electron pair into a pair of gamma rays, is governed by a quantity known as the classical radius of the electron, which is around 3×10^{-15} m. Put crudely, to annihilate, the positron and the electron have to sit on top of one another, and this is much less likely than a bounce-type collision. Thus, the positron can undergo many collisions, and thereby slow down in the neon, before annihilating. Indeed the positron kinetic energy is moderated in the neon to around 1 eV and many positrons (around 1% of the total source activity) reach the surface of the neon, where they can be emitted into the vacuum. In this respect a positron at the surface can be thought of as behaving truly as an antielectron, since we know from the photoelectric effect that energy must be supplied to remove electrons from materials. Radioactive sources are available with activities in the region of 1 GBq (or 10^9 disintegrations per second) so that it is possible to produce quite intense beams of positrons containing fluxes of several million particles per second.

Once the positrons are emitted into the vacuum at these low kinetic energies they are re-accelerated modestly (to about 50 eV) and are transported using solenoidal magnetic fields, which prevent the ensuing beam from expanding significantly transverse to its direction of motion. But now we have a problem if we wish to accumulate the positrons. Since they are derived from a radioactive source, the time interval between successive positrons is a random distribution about some mean. In other words, we don't know when the next positron will arrive. We could of course just set a trap for them and hope that some fell in by continuously opening and closing the trapdoor. But this would lead to costly reductions in flux. Fortunately, there is another simple solution.

We arrange a trap for them by forming the three-stage voltage well shown in figure 2. The well is coaxial with a 0.15 T magnetic field that provides transverse confinement. However, if a positron has sufficient kinetic energy to enter this arrangement, it will also be able to get back out the way it came in. Unless, that is, it can be persuaded to lose kinetic energy whilst it is in there. This is done by admitting molecular nitrogen gas to the centre of the first stage. (Note the pressure differential across the three stages.) About 30% of the positrons collide with the gas and lose about 10 eV in the process by exciting one of the molecular electrons to a higher orbital. If they do this on their first bounce they are caught and will continue to move to-and-fro, eventually performing two further excitation collisions and ending up in the third (lowest pressure) stage of the trap. Here they eventually reach thermal equilibrium with the gas, which is at room temperature.

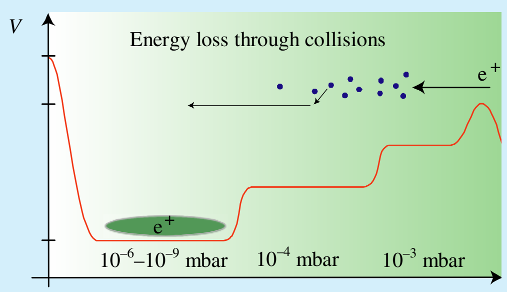

Figure 2. The three-stage voltage well configuration, plotted along the axis of the instrument, used to accumulate positrons via collisions with nitrogen gas. The positrons end up in the low potential/low pressure region. Note that when the nitrogen gas is turned off the pressure in this region drops to below 10^{-9} mbar, allowing the positrons to be transferred to the high vacuum antiproton enclosure.

In this manner positrons can be accumulated continuously in a region where the prevailing gas pressures mean that their lifetime against annihilation is of the order of 100 s. Accumulation rates in excess of one million positrons per second are typical and total numbers around 200 million can be gathered in a 3–4 minute cycle. The total positron number saturates when the overall annihilation rate and the accumulation rate are equal. The underlying physics is the same as that of a capacitor charging; this really is a positron accumulator[2].

Once the desired number of positrons has been accumulated the nitrogen gas is pumped out, the positron section is opened to the antiproton trap and the positrons are flung from one side of the apparatus to the other. Although a few are lost en route, every 2 minutes 75 million positrons are recaptured and held in a small well adjacent to the antiprotons. The positrons, like their light matter equivalent the electrons, lose kinetic energy rapidly by emission of synchrotron radiation in the 3 T magnetic field that is integral to the antiproton trap. Thus, the positrons cool to 15 K and await the release of the antiprotons.

Anthihydrogen formation and detection

The electrical potentials that hold the anti-particles for antihydrogen formation are shown in figure 3(*b*) and are referred to as a nested trap [6]. Essentially the positrons are nested within a larger trap that confines the antiprotons, which, once released from their side well, are constrained to pass repeatedly through the positron cloud. The

[2] The number of positrons accumulated at a time t can be written as $N(t) = N(\infty)(1 - e^{-t/\tau})$, where τ is the positron lifetime. This can be compared directly to the capacitor charging equation, $Q(t) = Q(\infty)(1 - e^{-t/CR})$, where CR is the time-constant of the circuit.

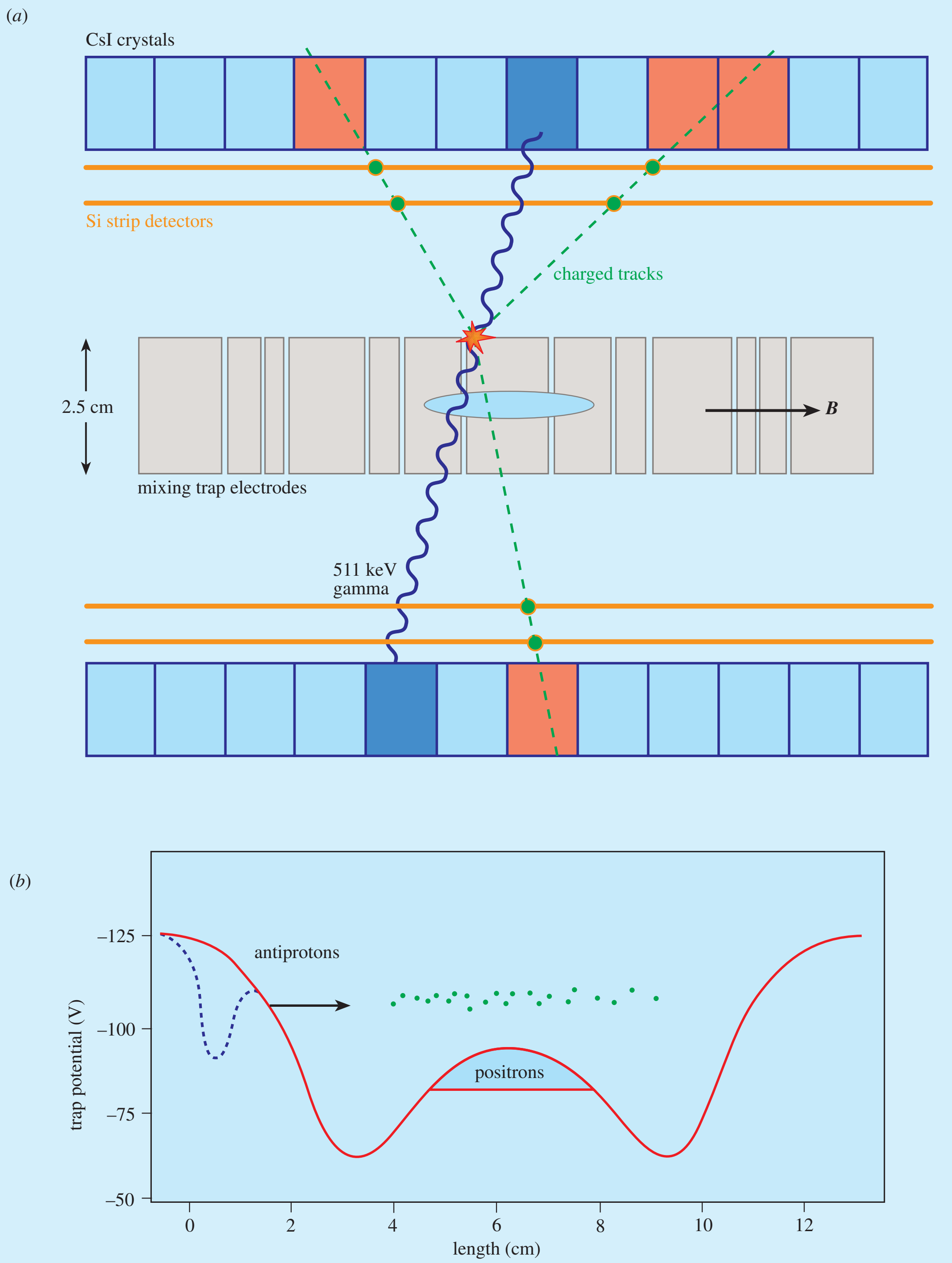

Figure 3. (*a*) Schematic side view of the antihydrogen production region. The cylindrical mixing trap electrodes lie along the axis of the magnetic field. Antihydrogen annihilation produces charged pions whose tracks are registered by the silicon strip detectors and 511 keV gamma rays that are counted by the scintillators (CsI crystals). (*b*) The on-axis electrical potential present in the mixing trap. Note the nested trap arrangement. The dotted curve shows the antiproton well prior to their release into the positrons.

arrangement of electrical potentials means that the antiprotons first enter the positron cloud with a kinetic energy of about 30 eV. As they did when passing through the electron cloud in the initial trapping procedure (see above), the antiprotons lose energy to the positrons, but importantly they can also form antihydrogen when the relative velocities of the positrons and antiprotons are close enough. They are thought to be able to do this by direct capture, in which the excess energy is emitted as a photon and/or via a so-called three-body process. Here, if the positron cloud is cold and dense enough, then two positrons might interact simultaneously with the antiproton such that one of them is capable of carrying away the excess energy.

Experiments by ATHENA have shown that antihydrogen formation begins a few tens of milliseconds [7] after the antiparticle mixing starts, and that the instantaneous rate of formation in the first second can be very high, more than 300 s^{-1}. Of the 10^4 antiprotons mixed with the positrons, about 1500–2000 can be persuaded to form antihydrogen over a mixing cycle lasting three minutes [8].

How do we know that antihydrogen has been formed? The two collaborations working at CERN chose very different schemes to check this, but both have found unambiguous evidence for antihydrogen. As mentioned above, we will concentrate on the method developed by ATHENA.

Once the neutral antiatom is formed it ceases to be confined by the fields used to hold its charged constituents. Thus it will quickly migrate to one of the metal electrodes that make up the charged particle traps, where it will annihilate on contact. This event comprises two distinct processes, since, by their nature, the positron and the antiproton annihilate separately. The main products of antiproton–proton annihilation (though note that the antiproton can also annihilate with a neutron, as long as the quark ‘arithmetic’ is done properly) are particles called pions, which can be positively or negatively charged or electrically neutral. With rest masses of 130–140 MeV, these objects are much lighter than the proton and antiproton (938 MeV) such that they are emitted with considerable kinetic energies as a result of the annihilation. The passage of the charged pions across thin silicon strip detectors (see figure 3(a)) is readily monitored because of the energy they deposit in the silicon, which results in a transient electrical output. Each pion must cross two layers of strips, such that back-extrapolation from at least three pions can be used to locate the annihilation vertex (to about ± 4 mm)[3]. This is shown schematically in figure 3(a) and reconstruction of a real event can be seen on the front cover of this issue.

So now we have pinned down the antiproton annihilation. Then the output of a bank of scintillators (which are used to detect gamma rays) is scanned to search for pairs that have fired within 5 μs of the vertex detectors, and the number of such events is plotted as a function of the cosine of the angle $\theta_{\gamma\gamma}$, the opening angle between the pair of gamma rays as measured from the vertex. Given that the characteristic low energy positron–electron annihilation event results in a pair of back-to-back gamma rays (shown schematically in figure 3(a)), each with energies of 511 keV (which is mc^2 for the electron and the positron) [1], the distribution should have a peak at $\cos\theta_{\gamma\gamma} = -1$, corresponding to $\theta_{\gamma\gamma} = 180^\circ$.

Figure 4 shows ATHENA’s first published data, revealing an excess of 131 ± 22 so-called ‘golden events’ around $\cos\theta_{\gamma\gamma} = -1$. This was the first unambiguous evidence for the creation of low energy antihydrogen. There are a few things to note about this plot and the number of events assigned to antihydrogen. The first concerns the combined detection efficiency for the antiproton vertex and the pair of gamma rays. The size of scintillators we were able to use meant that this detection efficiency was limited to only 0.25%. In other words, our stringent requirements to unambiguously identify the antihydrogen signal meant that we only counted 1 in every 400 of those produced.

The second thing concerns the pedestal of events at angles $\theta_{\gamma\gamma}$ other than 180°. Due to the inefficiency in gamma-ray detection it is clear that there will be many events in which one of the 511 keV gammas was detected but not the other. However, such events could contribute to the pedestal if another scintillator was excited.

[3] Unfortunately, due to space constraints, we were only able to utilize two layers of silicon detectors such that only straight-line extrapolations were possible. Thus, the curved trajectories of the pions in the 3 T magnetic field could not be monitored. This insensitivity dominated the spatial resolution of the event reconstruction.

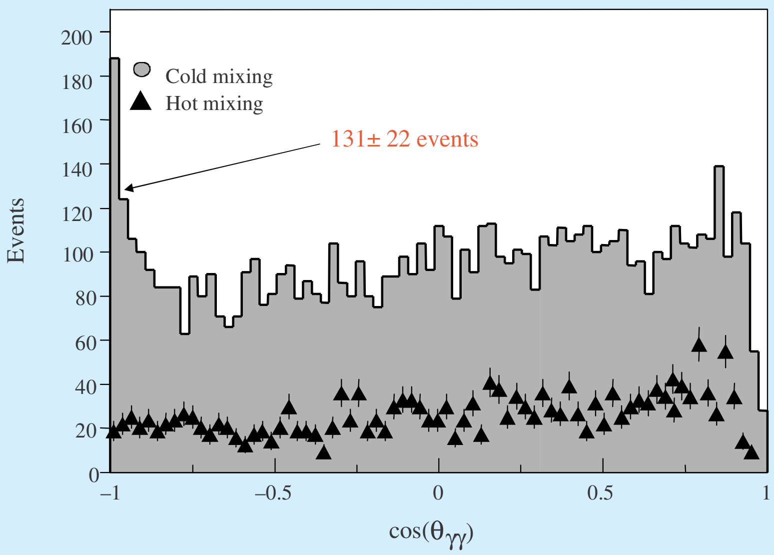

Figure 4. ATHENA's first sample of antihydrogen 'golden events', showing the excess in the region of $\cos\theta_{\gamma\gamma} = -1$ (see text). Cold mixing refers to a positron temperature of 15 K, whilst for hot mixing the positrons have been raised to about 3000 K. There is no antihydrogen formation at such high temperatures since the positron and antiproton velocities cannot match.

This could, for instance, be as a result of in-flight decay of the uncharged pions, which can produce high-energy gamma rays capable of mimicking a 511 keV signal. What we have found subsequently [8] is that the difference in the pedestal height between what we call cold mixing (which is when we leave the positrons at the ambient 15 K) and hot mixing (figure 4), when they are excited to about 3000 K by a radio frequency signal applied to one of the trap electrodes, is all a result of antihydrogen formation. We were thus able to deduce that, from all our runs at CERN in 2002 and 2003, ATHENA made over 2 million antihydrogen atoms. This is an encouraging start to antihydrogen research.

The future

The achievements to date in cold antihydrogen research have opened a new door for investigations of the subtle asymmetries that seem to lie at the heart of our universe. Aspects of this were described in the opening section of this article. However, there is so much more we need to know before experiments with antihydrogen offer competitive tests of current theories. In particular, it is likely that laser spectroscopy of antihydrogen will be a vital step in the right direction. Spectroscopy of hydrogen has recently reached fantastic precision for one line in particular, the two-photon 1S–2S transition [9][4], which has been determined to about 2 parts in 10^{14}, or roughly 46 Hz in a transition frequency of just under 2.5×10^{15} Hz. Amazingly, due to uncertainties in the properties of the proton, this level of precision is way beyond that achieved by theory. Comparisons of hydrogen and antihydrogen would be free of these uncertainties.

There are major challenges ahead. Currently we are not sure just how cold the antihydrogen is that we are producing. In other words, how low is its kinetic energy? We had, perhaps naively, assumed that once our positrons were cold, then antihydrogen at the same temperature would ensue. This seems not to be the case [10], and we may need to think of alternative antihydrogen production scenarios. Work on this has already begun [11].

[4] Recall that the transition 1S–2S is dipole-forbidden and cannot be a one-photon line. Thus, the emission of two photons is necessary for the hydrogen atom to decay from the 2S state to the 1S ground state. As a result the lifetime of the 2S state is long, at about $\frac{1}{8}$ s, such that the 2S state is often termed metastable.

Why do we need to have the antihydrogen so cold? The answer to this can be explained by everyday logic. If you want to describe the properties of an object, then it is easiest when that object is stationary. On the other hand, if the object passes at high speed, one sees blurred features and uncertainty ensues. It is the same with atoms and antiatoms. Thus, we should ideally create the latter at rest if we are to make best use of them for symmetry tests. Indeed, steps towards the ultimate goal of precision comparisons between hydrogen and antihydrogen are likely to involve attempts to trap ensembles of antihydrogen atoms, perhaps in a three-dimensional magnetic field minimum. However, such traps are shallow, with current magnetic technologies capable of trapping neutral species with kinetic energies equivalent to a temperature below 1 K. To trap antihydrogen efficiently we clearly would like to produce it at this temperature, or below.

In order to tackle gravity measurements on antihydrogen it is likely that even colder samples will be needed. The characteristic temperature scale here is set by the quantity mg/k, where m is the antihydrogen mass, g is the acceleration due to gravity and k is Boltzmann's constant. Inserting values gives, roughly, 1 $\mathrm{mK\,m^{-1}}$. In other words, raising antihydrogen by 1 m in the Earth's gravitational field costs the energy equivalent of 1 mK. It is likely that temperatures around this value will be needed if ballistic measurements involving antihydrogen are to be contemplated.

All of this poses severe experimental challenges, but a happy confluence of advances in atom trapping and laser cooling—almost all of them ideas that can, in time, be taken over to the antiatom domain—gives cause for optimism. Physicists working in this fresh and exciting field are already looking forward to a bright future, where challenge and discovery will continue apace.

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Michael Charlton is head of Physics at University of Wales Swansea and led the Swansea team that formed part of the ATHENA collaboration at CERN. ATHENA was the first experiment to produce copious amounts of cold antihydrogen. The Swansea group made many contributions to ATHENA, but particularly positron accumulation.