# Antihydrogen in a bottle

**Michael Charlton, Stefan Eriksson, C Aled Isaac, Niels Madsen and Dirk Peter van der Werf**

College of Science, Physics Department, Swansea University, Swansea SA2 8PP, UK

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

## Abstract
We describe recent experiments at CERN in which antihydrogen, an atom made entirely of antimatter, has been held in a magnetic minimum neutral atom trap and subjected to microwave radiation to induce a resonant quantum transition in the anti-atom. We discuss how this, the first experiment to observe an interaction between an antihydrogen atom and a photon, was achieved. We provide some background to antimatter physics and cover aspects of the current motivation for our experiments.

## Introduction

$2\,466\,061\,413\,187\,035 \pm 10$ Hz. This is the staggering precision, 4.1 parts in $10^{15}$, with which the frequency of the transition between the ground state of hydrogen and its first excited electronic state is known [1]. Such accuracy is reached by laser spectroscopy, and the result provides a touchstone for fundamental physics and metrology. The technique deployed involves two-photon excitation from the ground 1S state, to the so-called metastable (intrinsic lifetime around an eighth of a second) 2S state. The two photons are arranged to excite the hydrogen atom from counter-propagating beams that serve to cancel the first order Doppler shift due to the motion of the atom, which would otherwise blur the transition.

Whilst studies of hydrogen are important in their own right, for our purposes it is comparisons with the same transition in antihydrogen that hold

promise for the discovery of new phenomena in physics. In an earlier paper in this journal [2], we described how antihydrogen had been made in a controlled fashion. Here, we give an update for this field, made within the framework of the ALPHA antihydrogen collaboration at CERN [3], as we move towards the first comparisons of the properties of antimatter with those of matter. But, first, we answer an important question. Why should we bother to do this?

## The trouble with antimatter

There are many fundamental mysteries concerning the make-up and evolution of the Universe, which cannot be explained by the laws of nature we already know. Examples include dark matter, which seems to account for 83% of the material in the Universe, or 23% of the full mass–energy content when dark energy, which is reputed to pervade space–time, is included. Another conundrum facing physics is the apparent lack of antimatter in the Universe—at least as we view it from Earth. Why this is a problem stems from considerations of symmetry.

Antimatter is buried very deep in physics. The concept first arose in a consistent way

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(though there had been earlier speculation by Schuster [4], and probably others) with the work of the great British physicist Dirac (see, e.g., the accessible discussions given by Kragh [5] and Farmelo [6]). Dirac, working in the late 1920s, was able to successfully unite the young science of quantum mechanics with Einstein's theory of special relativity. When he did so, he obtained a great surprise. He found that the solution of his quantum equation (now known as the Dirac equation) for the energy, $E$, of an isolated, motionless, electron in free space was given by $E = \pm mc^2$. This looks like Einstein's famous formula for the rest mass–energy of a particle of mass $m$, with $c$ familiar as the speed of light—except that one of the solutions is for negative total energy. Dirac and others quickly found that this solution could not simply be ignored as being unphysical, as these negative energy state electrons had to be included in calculations for consistency. It took two–three years to sort out what the negative energy states implied. In a remarkable paper in 1931 (in which he was attacking a completely unrelated problem as to why electrical charge seems to come in lumps of magnitude $e$), Dirac [7] made the following astonishing prediction. '. . . [they] would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of them in nature, on account of their rapid rate of recombination with electrons, but if they could be produced experimentally in vacuum they would be quite stable and amenable to observation.' And so the positron was born, and it was discovered soon after by Anderson [8]. Perhaps even more amazingly, a few lines further down his paper, Dirac reasoned that (leaving the photon out for now) the only other particle known at the time, the proton, must also have an antiparticle, and he predicted the existence of the antiproton.

The rest, as they say, is history, but it certainly was not straightforward. By the late 1950s the antiproton had been discovered, but a slew of other particles were beginning to emerge (for instance, muons, pions and neutrinos). Classifying these objects into what eventually became known as the standard model was to occupy many minds for several decades. However, what did become clear was that each type of particle has an antiparticle associated with it (with a few exceptions, such as the photon, which is its own antiparticle). The understanding developed that there is a kind of symmetry between matter and antimatter which means that their properties, such as mass and charge, should either be the same (e.g., mass), or equal and opposite (e.g., charge).

Thus, it became conceivable that an entire Universe could be constructed from either matter or antimatter—perhaps both. It seems perfectly feasible to have everything from planets to plants, and from galaxies to glow-worms (and so forth) made from antimatter. So, do such things exist? How would we know? If the symmetry between matter and antimatter is exact, the light emitted by a star made entirely from antimatter would be identical to a similar matter star. However, any large-scale cosmic collision between a region made from antimatter and one comprised of matter would surely have a signature. The annihilation energy released would be visible to us on Earth. The problem is that we have never witnessed such a phenomenon. Certainly, in our own galaxy we are quite sure that there is no bulk antimatter present. And no matter how hard we look into the depths of space–time, we see no evidence for antimatter. And this is the trouble with antimatter. The laws of physics insist that it has to exist, and indeed it does, but there seems to be none out there. Whenever we make antiparticles down here on Earth by pumping in energy ($E = mc^2$ again), we have to balance the matter–antimatter ledger, and equal amounts of both are produced. And we expect that the same was true at the birth of the Universe, the event known as the Big Bang. So what happened to the antimatter? We are not sure. Although we have found some unusual reactions of very short-lived particles that had a fleeting existence after the Big Bang and that favour matter over antimatter, they are many orders of magnitude short of being able to account for even the visible matter in the Universe.

What we seem to be sure of is that most of the matter created in the Big Bang did annihilate with the antimatter that was also present. The visible Universe is made from what was left over, only about one part in $10^9$. So, at some time during the cooling of the Universe after the Big Bang, first the anti-quarks and then the positrons seem to

have disappeared. But we do not understand why. Nevertheless, it seems that when the Universe cooled sufficiently to form atoms, there were no antiparticles around to allow antihydrogen to be formed. In searching for an explanation of what happened to all the antimatter—or perhaps, closer to home, why any matter was left over to make us—one way is to explore the behaviour of particles at ever higher energies, moving as far back as we can towards the conditions after the Big Bang. However, we have chosen a different route, and one that involves making antihydrogen, the atom the Universe did not get a chance to manufacture on its own. Eventually, we want to study the properties of antihydrogen with the same (or better) precision than that mentioned at the start of the paper for hydrogen. Did the Universe leave an imprint of matter–antimatter asymmetry buried deep within the spectra of these two most fundamental of atoms? The remainder of this paper will be an update on our progress.

## Making a magnetic bottle

In order to attempt precision spectroscopy of antihydrogen, we have to make it by carefully mixing the positrons and antiprotons. We describe how this is achieved below. But simply making antihydrogen is unlikely to enable detailed study of its properties if it cannot be interrogated for long periods. It is easy to understand why this is so: the longer one looks at something, the more likely it is that finer details are resolved. This can be stated precisely in physics and there is, at least up to a well-understood natural limit determined by the energy–time uncertainty principle, an inverse relationship between the precision with which the frequency of an atomic transition can be measured and the length of time over which the atom is observed.

Thus, in order to study antihydrogen precisely, it seems necessary to bottle it up. And this also has the desirable effect of preserving this rarest of elements if the bottle prevents the antihydrogen from striking matter and annihilating. But how should this be done?

It is one thing to use electric and magnetic fields to confine the charged antiparticles (see below), but these cannot work in the same way for antihydrogen, which is electrically neutral. Fortunately, antihydrogen, like hydrogen, can feel

small forces due to magnetic fields that vary in space, since they have a property known as a magnetic moment. This arises because the positron orbiting the antiproton can be thought of as a tiny current loop, which will align itself either in the direction of the field, or opposite to it. This turns out to be related to a quantum property with the name spin. If the magnetic moment is given by $\mu_B$, then the change of energy of the atom, $U$, in a field $B$ is given by $U = \pm \mu_B B$. The plus sign in this equation indicates that the energy level rises with the magnetic field, and it turns out that these atoms have their moments aligned anti-parallel to the field. Conversely, the negative sign means that the energy drops and the moments of these atoms are in the field direction. In figure 1 we present what is known as the Breit–Rabi diagram of ground state antihydrogen (which for the present purposes is taken to be identical to that of hydrogen), which shows how the energy levels behave when a magnetic field is applied.

Let us first concentrate on those atoms whose internal energies rise in the magnetic field, with a higher field corresponding to a larger change. This energy has to come from somewhere, and since total energy is conserved it is at the expense of the kinetic component. Thus, as these atoms move towards a stronger magnetic field they will slow down, and if they have a low enough kinetic energy to start with they will be turned round before they reach the wall and be bottled. It is these antihydrogen atoms that we can keep and study, though currently they need to have a kinetic energy equivalent of about 0.5 K (i.e., around 50 $\mu$eV) or lower before we can trap them.

What of the atoms whose internal energies fall as the field rises? These atoms are attracted to the higher field and immediately migrate to the wall of the trap and are lost. Why this effect can be useful we shall see below, when we describe what the introduction of microwaves can do to trapped antihydrogen.

So now we know that if we can create a magnetic dish, or more properly a configuration of magnets whose combined fields create a minimum in all three spatial directions, then we can form a trap for neutral atoms, as long as they have low enough kinetic energies. Figure 2 shows a schematic illustration of the inner part of the ALPHA apparatus. For the moment, note
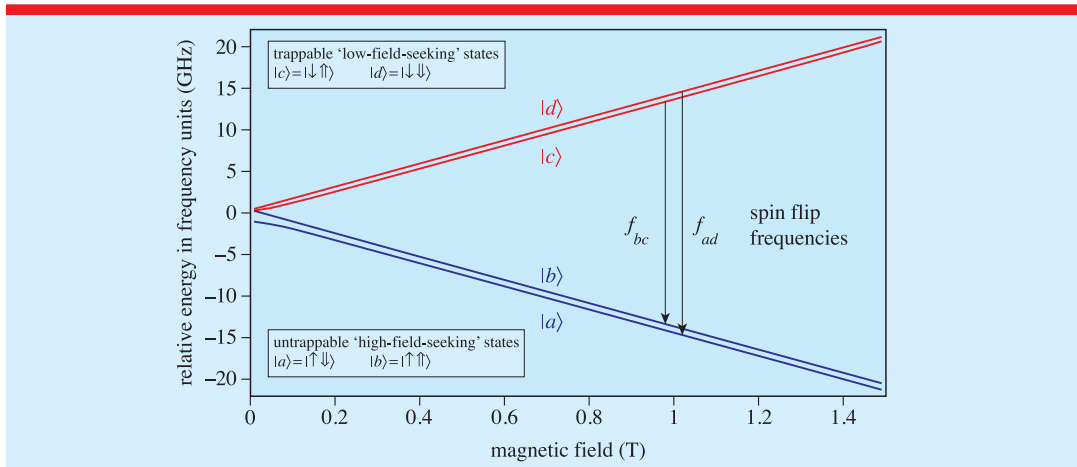
**Figure 1.** The Breit–Rabi diagram for ground state antihydrogen showing the low- and high-field seeking states. The *y*-axis gives the energies of the states relative to the no-field case in frequency units of GHz (i.e., the actual energy divided by Planck's constant), with the *x*-axis showing the required strength of an applied magnetic field in T. The arrowed notations refer to the spins of the positron (single arrow) and the antiproton (double arrow). The combination of directions for these two spin-1/2 particles means that there are four states in total. The vertical lines show the quantum transitions that are allowed between the upper (trapped) and lower (untrapped) states.
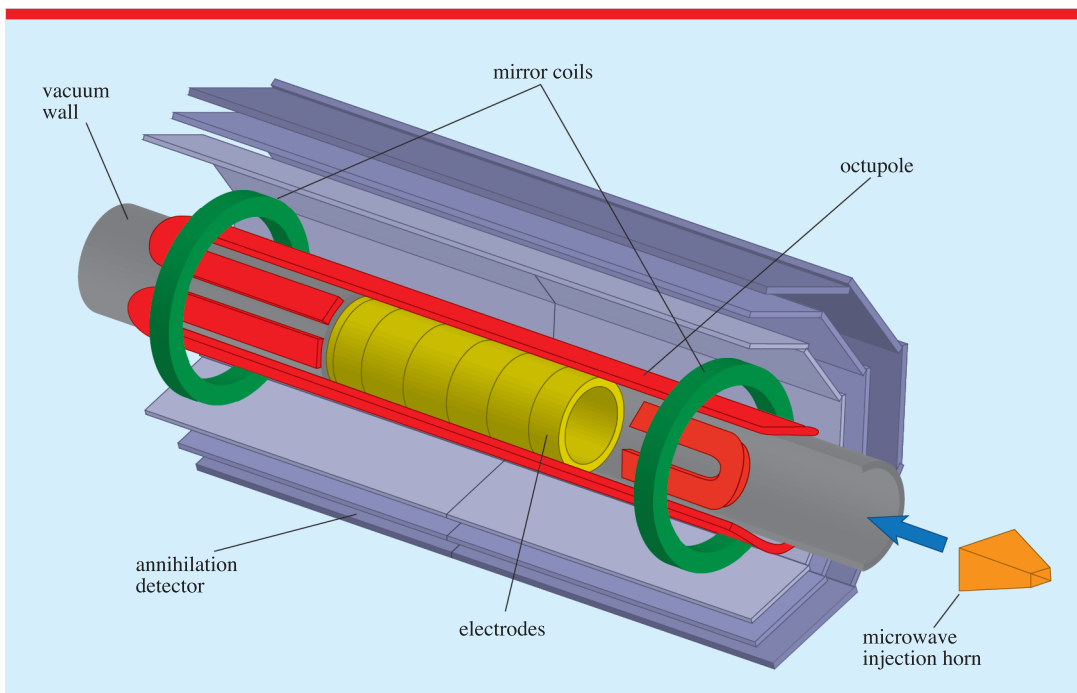


**Figure 2.** Schematic diagram of the ALPHA apparatus showing the electrodes that form the antiproton and positron traps and the coil system that provides the magnetic field that captures some of the antihydrogen atoms. The annihilation detector used to register antihydrogen annihilations on the electrode system (which is also the wall of the neutral trap) is shown on the outside. Note that the system parts are not drawn strictly to scale.

in particular the arrangement of coils: a pair of mirror coils separated along the axis of the system, and a coil in an octupolar form wound around the outer wall of the vacuum system that houses the electrodes. Powering the mirror coils creates an axial magnetic field minimum, whilst a circulating current in the octupole does the same in the radial direction.

The coils themselves are wound from state-of-the-art superconducting wires and carry many hundreds, or even thousands, of amps. Even so, the maximum field difference between the centre of the magnetic trap (which is the axis of the system) and the wall, which lies only 2 cm away, is just below 0.8 T. Given that the magnetic moment of the antihydrogen in its lowest state is the Bohr magneton (around 0.67 K T$^{-1}$), the effective neutral atom trap depth is, as mentioned above, just over 0.5 K.

This sets a great challenge for the experiment. We have to make, *in situ*, some antihydrogen atoms with kinetic energies around, or lower than, this amount to have any hope of capturing them. We now describe how this was achieved.

## Brewing antihydrogen for the bottle

In our previous paper [2], we summarized how antihydrogen atoms can be made by mixing clouds of antiprotons and positrons under well-controlled conditions. We recap here. CERN has developed many remarkable machines and techniques over the years, including the unique capability to decelerate and store beams of antiprotons. Antiprotons are made according to the reaction $p + p \rightarrow p + p + p + \bar{p}$ by slamming a pulse of energetic (about 26 GeV) protons into a fixed target. They are captured at a few GeV of kinetic energy by a machine known as the antiproton decelerator (AD), in which they are decelerated to a kinetic energy of just over 5 MeV before being ejected to our experiment in a burst around 200 ns in duration. When they arrive at our apparatus they pass through a thin foil in which they lose more kinetic energy, and some of them emerge at low enough energies to be captured in a device known as a Penning trap. This instrument is vital for the creation of antihydrogen, so it is worth spending some time describing how it works.
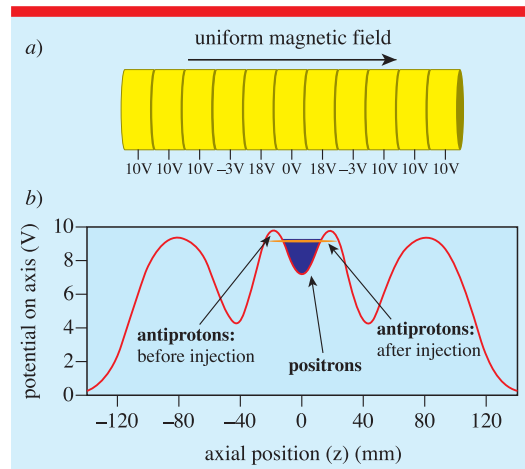


**Figure 3.** (a) A schematic diagram of the Penning traps used in ALPHA. The voltages applied to each of the cylindrical electrodes are shown, which together create the electrical well structure illustrated in the lower panel. (b) The potential on the axis of the instrument and the positrons and antiprotons held in their respective wells. A uniform magnetic field of 1 T is superimposed to trap the particles in the radial direction.

A schematic illustration of a Penning trap is given in figure 3(a). Entire textbooks and long review articles have been devoted to the description of these devices (see also [3, 9]), which have found major applications in physics and chemistry. For the present purposes, there are a few key points to note. The first is the (constant for the moment) magnetic field that runs along the axis of the system, and which is typically at least 1 T in magnitude. Charged (anti)particles perform a spiralling motion as they move along the axis of such a magnetic field, which provides their confinement in the radial direction.

The next important feature is the electrode system, which was also included in figure 2, and which is used to provide the axial confinement of the antiparticles by applying appropriate voltages to them. An example of a series of confining potential wells for positrons and antiprotons, as used in antihydrogen production, is shown in figure 3(b). Thus, the combination of the magnetic and electric fields present in the Penning trap can be used to confine the antiparticles in an ultra-high vacuum chamber where their interaction with matter is almost entirely eliminated. We have been

able to store the charged antiparticles for many hours for some time now. We will get to our recent progress in storing antihydrogen soon, but first a word about the positrons.

The reader can refer again to the 2005 paper for details [2], but it has become routine over the last 40 years to produce beams of low-energy positrons in vacuum, using specially prepared surfaces and moderating the kinetic energies of $\beta^+$ particles emitted from isotopes such as $^{22}$Na. More recently, say for 10–20 years or so, techniques to capture the low-energy positrons in Penning-type traps have been developed—exactly the kind of source required for antihydrogen production, as described in [10].

This is all well and good, but the difficulty remains in trying to make antihydrogen so that at least some of it is cold enough to be held in our weak magnetic bottle. It has been possible to make low-energy antihydrogen since 2002 [11, 12], but new techniques have been deployed to achieve antihydrogen trapping. Foremost, the antiparticles must be cold before they are mixed. To achieve this we have borrowed a technique familiar in the field of cold-atom physics, namely evaporative cooling. An accessible account of this can be found on the web [13], from where it is clear that the physical principles involved are very general; the cooling of a cup of coffee or tea is usually cited to justify this.

Our positrons and antiprotons are held in shallow potential wells, as shown in figure 3(b). We cool them by reducing the size of the well in steps. At each step, the hottest particles in the distribution, which is a Maxwell–Boltzmann distribution characteristic of a particular temperature $T$, escape (i.e., evaporate) from the well. Those particles remaining collide with one another and, with the hottest ones absent, they re-equilibrate to a lower temperature. We have been able to reach temperatures as low as 10 K using this technique. Although this is much higher than the 0.5 K depth of the antihydrogen trap, again there is a distribution of energies within the thermal cloud, and a small fraction of the antiparticles will have a kinetic energy equivalent of 0.5 K or below.

With the antiparticles cold in their respective well, they still have to be brought together in a way that does not result in their kinetic energies increasing, or at least in as small a rise

as possible. In our earlier experiments [2, 11], the antiprotons were launched into the positron clouds by manipulating them using well depth changes of 10–20 V. Perhaps unsurprisingly, we found that the antihydrogen we produced had kinetic energies in excess of that expected from the $T$-value of the positrons [14]. It is not feasible to create a magnetic trap for such energetic antihydrogen, so a new method of mixing had to be devised.

The antiprotons in their potential well behave like a bunch of simple harmonic oscillators and they bounce to and fro along the axis of the system, with a particular frequency, say $f_z$. In our case, $f_z \sim 410$ kHz, corresponding to a period of just under 2.5 $\mu$s. To try to get them out of the well, one can attempt to drive them by exciting the axial motion using a voltage oscillation at $f_z$. The problem with this is that as the antiprotons are driven harder, the amplitude of the oscillation increases and eventually the simple harmonic approximation to the motion (which is for small amplitudes) breaks down. What happens is that the period of the motion becomes longer, so that the drive voltage at $f_z$ is no longer in resonance, and eventually the motion will damp down again. This sort of cycle will repeat itself, but the antiprotons will never be driven from the well.

However, if the frequency of the drive motion is varied with time in a particular way, a type of locking phenomenon can occur. The idea is to start the drive at a frequency, $f_d$, above $f_z$, and lower it to a frequency below this value. This is a technique called chirping, and in our case a typical starting value for $f_d$ was around 420 kHz and it was chirped at a rate of 200 MHz s$^{-1}$, with the sweep ending after just 0.3 ms at a final frequency of 360 kHz. As $f_d$ passes through $f_z$, the antiprotons lock to the drive and follow it into the so-called non-linear regime as the amplitude of oscillation grows. Eventually, the antiprotons are ejected from their well in a short burst and enter the adjacent positron cloud. They do so by gaining the minimum kinetic energy possible for escape, and this excess is quickly dissipated in the positron cloud. This is a variant of a phenomenon known as autoresonance, and examples of this kind of behaviour can be found in many types of oscillatory systems. An interesting introduction to this effect has been given elsewhere [15],

and the ALPHA collaboration has published a research paper on the realization of this technique [16].

Once inside the positron cloud, many of the antiprotons promptly form antihydrogen. It turns out that the positron cloud is sufficiently dense that antihydrogen forms in a collision involving an antiproton and two positrons, i.e. $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$, where one of the positrons binds to the antiproton, with the other recoiling in a manner that conserves energy and momentum. Therefore, the antihydrogen atoms are formed directly in the neutral atom trap, but via the two-positron reaction described above they are initially in very highly excited states. This is because the energy exchange occurs between the two positrons that collide in the vicinity of an antiproton. This is a quasi-elastic encounter of two particles of equal mass. As such, the energy exchanged will be of the same order as the kinetic energy of the positrons, i.e. around $k_B T$ (with $k_B$ being Boltzmann's constant), which means that one of the positrons will be bound by a similar amount. To put this into perspective, typical binding energies are about 5 meV, which is to be compared to the binding energy of the ground state of 13.6 eV.

This is where the trapping of the anti-atoms comes to the fore. To perform measurements on antihydrogen to rival, for instance, those for hydrogen, the antihydrogen must be in its ground state. We calculate that by about 0.5 s, all of the excited antihydrogen we formed will have decayed to the ground state by the emission of a cascade of photons. Thus, our trap needs to catch as many antihydrogen atoms as it can, and hold onto them for at least the time taken for this cascade to occur.

What we have been able to achieve recently is to trap a few hundred antihydrogen atoms (though typically only one at a time) and to hold on to them for periods of 1000 s or more if desired [17, 18]. In essence, once they are caught, the gas pressure is so low in our trap that there is little to disturb them and they remain trapped. With an antihydrogen atom in our trap, we are ready to perform experiments on it, as we are now sure that it has reached the ground state.
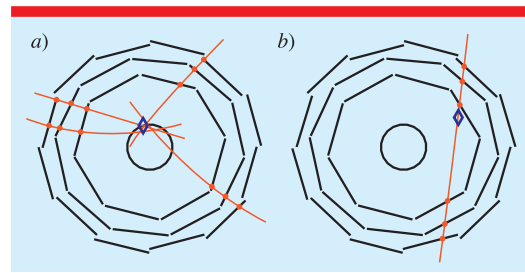


**Figure 4.** (a) A reconstructed antiproton annihilation event following the collision of an antihydrogen atom with the trap wall; the latter is shown as the inner black circle. This event has four tracks, with the vertex shown by the blue diamond. The positions where the pions traverse the pads of the silicon detector, which is shown here in section (see figure 2), are given as red dots. (b) The track of a cosmic ray which passed straight through the detector.

## Flipping microwaves

In order to perform an experiment, we have to be able to detect its result. Fortunately, the annihilation of an isolated antihydrogen atom when it hits matter is, relatively speaking, rather straightforward to register. When the antiproton in the anti-atom annihilates a small shower of particles known as pions is emitted. These particles have large kinetic energies, typically many tens of MeV or more, and for each annihilation event several of those emitted are electrically charged. Their high kinetic energy means that they can penetrate the material that is located between the annihilation point and the detector that surrounds the apparatus, as shown in figure 2. And those that are charged deposit energy in the detector. This instrument is based upon silicon strip technology, and has imaging capabilities such that it can pinpoint the positions at which the pions cross. The three layers of this detector allow us to reconstruct the pion tracks as they pass out of the apparatus and, if enough of them are registered (typically three or more), to find the so-called annihilation vertex.

Figure 4(a) shows such a reconstructed annihilation vertex, which is located (within the resolving power of the detector) on the walls of the electrodes, which form the inner trap (see figure 2). Figure 4(b) shows the signal a cosmic ray leaves when it traverses the detector, and we have to take care to reduce the influence

of these, which are a source of background for the experiment. The obvious and very different topology of the two types of event is one means of differentiating them.

But how do we know if we have an antihydrogen atom, or two, in the trap? One method is to empty the trap by lowering the magnetic fields and search for annihilations in a narrow time window as the trap depth drops. The coil system that provides the fields for the trap has been specially designed to be capable of allowing these very strong fields to be removed in a fraction of a second. Around 30 ms after shutdown is initiated, the trap depth has fallen to only a few per cent of its full value, and almost all of the antihydrogen atoms have escaped. Thus, we can search for annihilations in this time window, which further helps to reduce the effect of cosmic rays, which are randomly distributed in time. Thus, our signal of a trapped anti-atom is to record an event like that shown in figure 4(a) in the 30 ms after the magnet switch-off commences.

Refer again to figure 1 and recall that the two upper states, labelled $|c\rangle$ and $|d\rangle$, are the only ones that can be trapped. The magnetic field in the centre of our trap is close to 1 T in magnitude, so if we illuminate the anti-atoms with (as it turns out) microwave radiation at frequencies $f_{bc}$ and $f_{ad}$ the positron spin can flip. $|c\rangle$ states will be transformed into $|b\rangle$s, whilst the $|d\rangle$s go to $|a\rangle$s; either way, the result is a state that cannot be trapped. The anti-atoms will exit the trap and annihilate on the wall very promptly. Thus, if after microwave illumination we empty the trap using the magnet ramp down method described above, we should find the trap empty if we have excited a resonant quantum transition in the antihydrogen. And this is what we have found. We performed just over 100 trials with microwaves on and off resonance, and compared the counts we detected when we removed the trap. With microwaves off resonance, we found that 23 anti-atoms survived, but on resonance, only two [19]. Clearly, the trap had been more-or-less emptied.

But we were able to go further. By refining the analysis of the output of our silicon imaging detector, we could isolate the annihilation signal of the de-trapped antihydrogen when the microwaves were on resonance. This is illustrated in figure 5, which shows excess counts in two 15 s time bins in which the
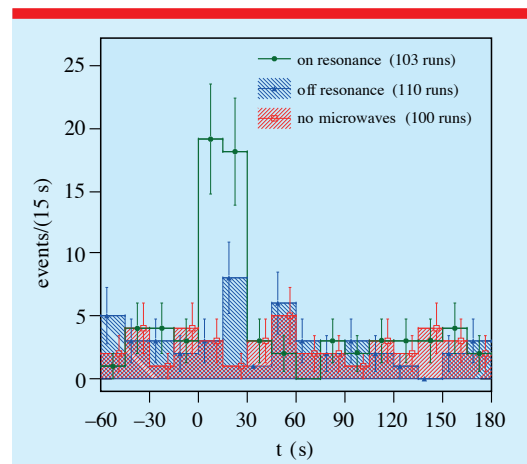


**Figure 5.** Annihilation events as a function of time elapsed after the start of the microwave illumination. The uncertainties shown are due to counting statistics. The excess events on resonance are due to the microwave-induced annihilations on the trap walls.

microwaves were on resonance at $f_{bc}$ and $f_{ad}$. No such counts can be seen with the microwaves off, or with the frequency of the microwaves shifted to an off-resonance value. Thus, the ALPHA experiment has been able to demonstrate not only that antimatter in the form of antihydrogen can be created, but that it can be stored for long periods. Furthermore, we have observed the first resonant transition in any anti-atom.

## What is next?

Now that we are sure that we can hold on to antihydrogen long enough to perform experiments on it, we want to increase the precision of the measurements. To ensure that this first resonance experiment was successful, the microwave frequency was scanned, covering the resonance line in a 15 MHz-wide band. This obviously limits the accuracy of the measurement.

The ALPHA apparatus shown in figure 2 was designed primarily with the goal of demonstrating that antihydrogen could be trapped, though we were able to introduce the microwaves via the horn shown in the figure, through which the radiation was funnelled. We are currently building a new version of the apparatus. This will have very carefully designed and variable magnetic fields to help keep the microwave resonance as narrow (theoretically) as possible. We will also be

able to introduce laser light into the antihydrogen trap. Hopefully, we will soon have the capability to make measurements of transitions between the 'positronic' states of antihydrogen to compare with, as described at the start, the staggering precision with which the corresponding electronic properties of hydrogen are known.

## Take a look at this

Our experiment has been simulated for us by GRALLATOR, a UK company dealing in the application of mathematics and science to industry and education using modelling, simulation and software. Check it out on the ALPHA website [3] and watch the antihydrogen being trapped, and then wait for the microwaves to flip the positron spin to release the caged anti-atom.

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**Mike Charlton** was brought up in the north-east of England and studied physics at University College London, UK. He remained there for over twenty years before taking up a chair in experimental physics at Swansea University, UK in 1999. He recently held an EPSRC senior research fellowship and is a fellow of both the Institute of Physics and the Learned Society of Wales.

**Stefan Eriksson** studied physics at the University of Helsinki, Finland. He was a post doc at Imperial College London, UK from 2003. In 2007 he moved to Swansea University, where he is currently a senior lecturer of physics.

**Christopher 'Aled' Isaac** grew up in the Welsh town of Merthyr Tydfil, going on to study for an MPhys at the University of Wales, Swansea. He completed his PhD at Swansea University as part of the experimental physics group and is currently a post doc in the same group.

**Niels Madsen** reader in experimental physics at Swansea University, studied physics at Aarhus University in Denmark from where he was also awarded a PhD. He moved on to work on antihydrogen at CERN, securing a Danish Steno Fellowship before he finally took up a position as lecturer at Swansea University in 2005. He has recently held a Royal Society Senior Leverhulme research fellowship and is a fellow of the Institute of Physics.

**Dirk Peter van der Werf** studied physics at the University of Groningen, Netherlands before taking up a post doc position at Royal Holloway College, University of London, UK. Since 1999 he has been working on antihydrogen, first at University College London and subsequently at Swansea University. He holds the position of reader and is a Leverhulme research fellow.