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Review

Cold antihydrogen: a new frontier in fundamental physics

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The year 2002 heralded a breakthrough in antimatter research when the first low energy antihydrogen atoms were produced. Antimatter has inspired both science and fiction writers for many years, but detailed studies have until now eluded science. Antimatter is notoriously difficult to study as it does not readily occur in nature, even though our current understanding of the laws of physics have us expecting that it should make up half of the universe. The pursuit of cold antihydrogen is driven by a desire to solve this profound mystery. This paper will motivate the current effort to make cold antihydrogen, explain how antihydrogen is currently made, and how and why we are attempting to trap it. It will also discuss what kind of measurements are planned to gain new insights into the unexplained asymmetry between matter and antimatter in the universe.

Keywords: antimatter; antihydrogen; antiprotons; positrons; charge, parity and time theorem

1. Introduction

Antihydrogen is the antimatter counterpart of hydrogen. As hydrogen is made up of one proton and one electron, this implies that antihydrogen is made up of one antiproton and one antielectron, the latter also known as the positron. The existence of antimatter was first predicted theoretically by Dirac (1931). Soon thereafter, Anderson (1933) identified the positron in a cloud chamber experiment investigating cosmic rays. The antiproton however, being much more massive, was only discovered in 1955 by Chamberlain *et al.* (1955) at the 6 GeV Bevatron machine at Lawrence Berkeley Laboratory, USA.

However, it was not until 1995 that researchers working at CERN in Geneva, Switzerland, succeeded in making the first atoms of antimatter, the first antihydrogen (Baur *et al.* 1996). Making antihydrogen is made difficult by the need to obtain antiprotons such that the determining step was the advent of the low energy antiproton ring, LEAR, at CERN. The first study, in which only nine antihydrogen atoms were made at relativistic speeds, left no possibility for further exploration of the properties of atomic antimatter. A similar experiment in 1997 at Fermilab near Chicago in the USA succeeded in making about a hundred

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antihydrogen atoms, but again at relativistic speeds (Blanford *et al.* 1998). LEAR was discontinued and a new antiproton ring, the antiproton decelerator (AD), was built at CERN. It was at this unique machine that researchers in first the ATHENA and then the ATRAP collaborations succeeded in making low energy antihydrogen in 2002 (Amoretti *et al.* 2002; Gabrielse *et al.* 2002). Not only did the new experiments succeed in making the anti-atoms in a low energy trap environment, but the production rate, at least in the case of ATHENA, was many orders of magnitude higher than previous experiments, being several thousands of anti-atoms every few minutes (Amoretti *et al.* 2004). The author was part of ATHENA at the time, and of its present successor, ALPHA. Thus, this article will mostly focus on experience gained from these experiments.

The quest for antihydrogen is motivated by the current failure of physical theories to completely describe the universe as we see it. There are a number of fundamental problems in modern physics that remain to be addressed, and for which CERN has also built the new Large Hadron Collider. An overarching problem is that the theory of the very small, quantum mechanics, and the theory of the very large, Einstein's general relativity, are not fully compatible. This means, for example, that we cannot achieve a complete, self-consistent, description of black holes (Barceló *et al.* 2009). In fact, we do not really know if they truly exist in the form that Einstein's theory predicts, as the extreme conditions in some black holes require a quantum mechanical version of gravity, which we do not have. But it is not only black holes that pose problems. Even more extreme conditions existed in the early universe, directly after the Big Bang. It is thought that conditions in the early universe provided the origin of the current asymmetry between matter and antimatter. Antimatter is formed when converting energy to matter. Such a conversion follows Einstein's famous equation, which states that $E = mc^2$, where E is the energy, m is the mass and $c = 300\,000\,\mathrm{km\,s^{-1}}$ is the speed of light in vacuum. When energy (in the form of photons) is converted to matter, equal amounts of antimatter appear. Thus, to make an electron, one needs at least twice the energy of a single electron, as a positron is also necessarily made (in practice, more is needed as momentum needs to be conserved as well as energy). This process, called pair production, has so far never failed when observed. Thus, as the universe started out with no matter, the universe of today should contain equal amounts of matter and antimatter. However, extensive searches for evidence of antimatter in cosmic rays as well as by other means have been unsuccessful. The universe thus seems devoid of antimatter.

The mirror-like symmetry between matter and antimatter described above goes further than the expectation of equal production rates. In fact, the charge, parity and time (CPT) theorem which is a fundamental consequence of quantum field theory, states that under the combined symmetries of Charge conjugation (changing the sign of all charges), Parity transformation (exchange of left and right) and Time reversal (letting time go backwards), all physical laws remain the same. If we apply this transformation on a hydrogen atom we end up with antihydrogen, and as all laws remain the same, any experiment on the antihydrogen atom should give the same result as the corresponding one on the hydrogen atom. In other words, the energy levels of antihydrogen should be *exactly* the same as those of hydrogen. If not, some parts of quantum field theory will have to be reformulated.

To date no experiment has measured any part of the antihydrogen spectrum, or even detected photons interacting with antihydrogen. However, CPT symmetry has been tested in other cases. Measurements have been done on the bound state of a positron and an electron, called positronium, and on helium atoms where one electron has been replaced by an antiproton. None of these investigations have detected a violation of the CPT theorem. However, antihydrogen would be the first pure antimatter system to be probed, and hydrogen is the simplest and one of the best studied atoms of all, making detailed comparisons with antihydrogen one of the most sensitive probes of the CPT theorem (Shore 2005). It is expected that no violations of CPT will be found. If a violation were found, it would be sensational.

2. Making antihydrogen

As stated above, the first antihydrogen was made in beam experiments at relativistic speeds and was not easily amenable to observation. To make low energy antihydrogen it is necessary to trap and cool its constituents, positrons and antiprotons. Techniques for trapping, cooling and accumulating large numbers of positrons were pioneered by Cliff Surko's group at UCSD (Murphy & Surko 1992), and devices based on these principles are now routinely supplying tens of millions of positrons to antihydrogen experiments. Techniques for trapping, cooling and accumulating antiprotons were pioneered by Gabrielse *et al.* (1986, 1989) working at the aforementioned LEAR facility at CERN.

(*a*) *Trapping antiparticles*

Antiprotons are produced by letting a burst of about 10^{13} protons with an energy of 26 GeV[1] collide with a fixed target. The massive kinetic energy of the incoming beam allows for the formation of antiprotons. Some of the antiprotons produced are collected and fed into the unique AD ring, where they are decelerated and cooled after which they are sent to one of the various experiments located in the AD hall. The AD typically delivers 30 million antiprotons every 2 min at 5.3 MeV. However, this energy, which corresponds to a speed of approximately 10 per cent of that of light, is still much too high for controlled antihydrogen formation and further deceleration is required.

The most common way to finally decelerate the antiprotons towards trappable energies is simply by letting them pass through a foil, called a degrader. Passing through the foil the antiprotons collide with its atoms and lose kinetic energy. The process is not spectacularly efficient but it is very robust and cheap. After the foil, about half the antiprotons have annihilated, i.e. disintegrated on matter. Of the half that pass, a few parts in a thousand have energies in the low keV regime and can be trapped by quickly switching electrostatic fields in devices called Penning–Malmberg traps.

All charged particles in these experiments are trapped in Penning–Malmberg traps (figure 1) which use an axial magnetic field to confine the particles transversely, and an axial electric field to confine them axially. In the experiments

[1] An eV is the energy a particle of charge e gains if accelerated across a voltage difference of 1 V. A GeV is a billion eV.

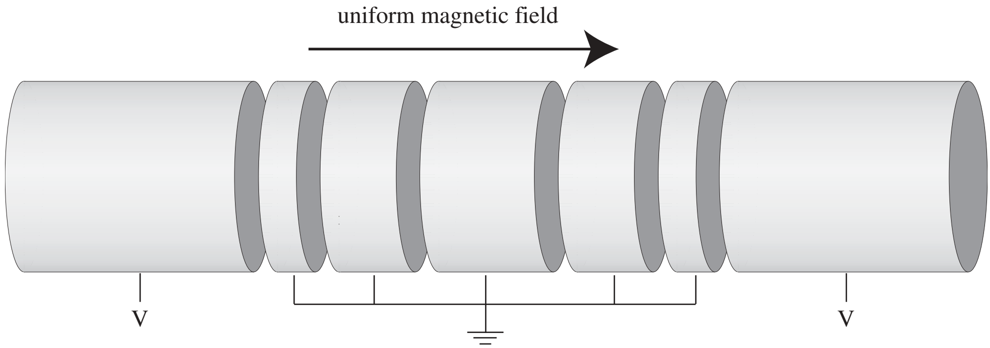

Figure 1. Example of a Penning–Malmberg trap similar to those used in the antihydrogen experiments. Particles are confined radially by a strong uniform axial magnetic field. Axially they are confined by the electric fields generated by biasing the conducting, but individually insulated, cylinders (called electrodes). In practice, more electrodes are needed for antiparticle manipulations and the ALPHA, ATHENA and ATRAP experiments use up to 50 individually controllable electrodes.

discussed here, the magnetic fields are in the range 1–5 T. Such strong fields cause the low-energy charged particles to have a small-radius cyclic motion in the plane perpendicular to the field (the transverse plane), thus preventing their escape. The axial field is generated by a set of conducting cylinders, called electrodes, coaxial with each other and the magnetic field. The electrodes can be excited to different voltages such that the resulting electric fields axially confine the charged particles.

Before the antiprotons arrive from the AD, a central region of the trap has been pre-loaded with electrons. The trap environment is cooled to cryogenic temperatures using liquid helium. Accelerated charged particles emit radiation, more so if they are less massive. Thus, the transverse motion of the electrons causes them to lose energy until they are in equilibrium with their surroundings; i.e. they cool. When the antiprotons arrive they are trapped in the same volume as the electrons, and will be indirectly cooled by them through collisions. Once cold, the kilovolt potentials needed to trap the incoming antiprotons can be lowered and more antiprotons can be accumulated, or the low energy antiprotons thus amassed can be used for experiments.

Meanwhile, the positrons have been accumulated elsewhere. In all current experiments the positrons are stored in a device external to the main traps of the experiments. The positrons, being much less massive than antiprotons, are easier to obtain and are derived from a sodium-22 radioactive source. Once sufficient numbers are available they are transferred to the main experiment, where they are combined with the antiprotons.

(*b*) *Antihydrogen formation*

There are several ways in which antihydrogen can be formed. The most successful method to date is to merge the clouds of antiprotons and positrons, prepared as described in §2*a*. Rather than making positrons and antiprotons interact directly, as will be described in more detail below, it is possible to

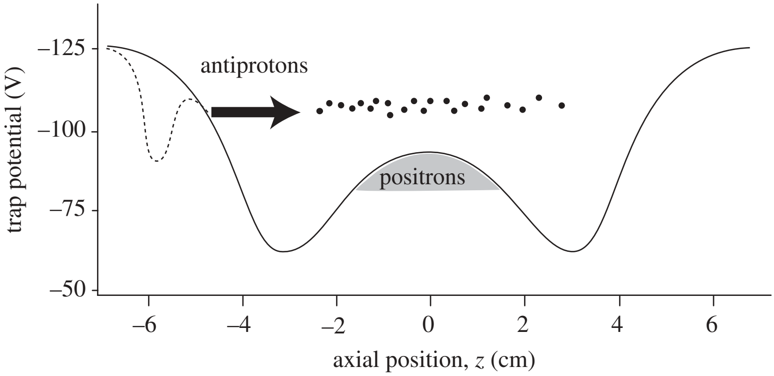

Figure 2. Axial electric potential used for mixing positrons and antiprotons; the so-called nested Penning trap configuration. Note the inverted ordinate axis. Positrons are stored in the central negative well before the arrival of the antiprotons. The antiprotons are then launched into the positrons and on successive passages they slowly cool by collisions with the positrons which cool through synchrotron radiation. Once the relative velocity is low enough an antiproton can trap a positron and form antihydrogen. Once formed the antihydrogen is not confined and will drift until it comes into contact with matter.

go through an intermediate step and make positronium, and allow that to collide with a cloud of antiprotons. If the positronium is formed in an excited state, as proposed by Charlton (1990), the cross section (probability) for making antihydrogen increases dramatically. This method was recently demonstrated by ATRAP (Storry *et al.* 2004), and has the major advantage that it is possible to control the final state of the antihydrogen, and possibly that it avoids various issues, described in more detail below, that arise when merging clouds of charged particles. However, until now, only a few antihydrogen atoms have been made in this way, and it is not yet clear if the advantages outweigh the low absolute efficiency.

Antiprotons and positrons are of course oppositely charged, but can be brought together in a simple double arrangement of the electric potential of the Penning–Malmberg trap. This configuration is often called a nested Penning trap (figure 2). The details of this procedure are important. In early experiments, the antiprotons were launched at a potential that made them pass easily (and at high energy relative to the temperatures of the cryogenic environment) through the positrons. The positrons are cooled by synchrotron radiation in the same way as the electrons, and the original idea was that collisions with the positrons would cool the antiprotons, which when cold enough would recombine with positrons and form antihydrogen. This worked very well, and was the method used for the first antihydrogen formed in 2002. However, it was later found that the antihydrogen formed in this way is quite energetic (Madsen *et al.* 2005). The reason for this is easy to understand. The rate determining factor for the recombination of a positron with an antiproton is their relative velocity. However, as antiprotons are approximately 2000 times more massive than the positrons, their velocity is small relative to that of the positrons, even when they are much more energetic. In fact, an antiproton with an energy of 2 eV has the same speed as that characteristic of an ensemble of positrons held at a temperature of 15 K. Thus, the antiprotons do cool through collisions with the positrons, but rather quickly the relative velocity of the species is entirely dominated by the velocity of the positrons. Antihydrogen can thus form by recombination of a 15 K positron and 2 eV antiproton almost as easily as if both particles were at 15 K. Antihydrogen is therefore quite likely to form from rather energetic antiprotons, which will contribute most of the kinetic energy of the antihydrogen. It is therefore quite likely to form very energetic antihydrogen using this method. This problem is now being addressed by instead loading the antiprotons into the side wells of the positron plasma. By slowly changing the potentials that confine the species they are brought together at the lowest possible relative energy.

(*c*) *Detection*

How can antihydrogen be detected if antihydrogen and hydrogen are mirror images and thus essentially indistinguishable? We happen to live in a matter universe, so detecting a single antihydrogen atom is fortunately relatively straightforward. By allowing the antihydrogen to collide with matter it will annihilate. When a positron annihilates with an electron it results in the release of two back-to-back 511 keV photons. Antiprotons can collide with both nucleons, protons and neutrons, and as they consist of antiquarks the result varies from event to event, but generally amounts to the release of a few charged particles called pions. The charged pions can be detected with high efficiency by position sensitive silicon detectors (similar to a CCD), and, by having a number of layers of these, the tracks of the pions can be reconstructed and their origin (the so-called annihilation vertex) can be determined. The photons are harder to detect and their energy must also be measured, thus they are completely absorbed on detection. Therefore, the location of the positron annihilation can only be fixed to lie on the line between the two points of detection. To detect an antihydrogen we therefore look for events where the antiproton annihilation vertex is time-coincident with two photons of the right energy detected to lie on a line passing through the annihilation vertex. In other words, we look for a time and space coincidence of the two types of annihilations. This was the method used by ATHENA for the very first low energy antihydrogen in 2002 (figure 3).

An alternative indirect method, first used by the ATRAP collaboration, is to strip, or field-ionize, the antihydrogen atom of the positron using a strong electric field and trap the resulting bare antiproton (Gabrielse *et al.* 2002). The number of antiprotons trapped in this way is therefore a measure of how many antihydrogen atoms were field-ionized. This method has the advantage that it is sensitive to the binding energy of the antihydrogen as the stripping field can be changed. However, due to the limited electric fields available in practice it only addresses very weakly bound antihydrogen, and owing to the typical geometry of these experiments it has a relatively low collection efficiency.

3. Trapping antihydrogen

There are currently two experiments racing one another to be the first to trap antihydrogen: ALPHA and ATRAP. As mentioned in §1, the ultimate goal is to probe the energy levels of the antihydrogen atoms. Trapping will allow accumulation of the anti-atoms, thus increasing the signal, and it will allow much increased interrogation times thereby increasing the precision of the measurement. Thus, trapping is seen as a prerequisite for high precision measurements. In current experiments, the antihydrogen only survives for a few microseconds before it collides with the trap walls and annihilates.

Antihydrogen, like hydrogen, can be trapped in a minimum of magnetic field strength due to its small magnetic dipole moment. A minimum of axial field strength can be created by two axially separated, but coaxial coils. The transverse field minimum can be created by a transverse multi-pole, of which the simplest is the quadrupole. This configuration is called a magnetic minimum trap, or neutral trap. The magnetic moment of the antihydrogen atom depends on which state it is in, but it is the smallest in the ground state, in which all the atoms will eventually find themselves. The trap depth for ground state antihydrogen is $0.76\,\mathrm{K\,T^{-1}}$ of field change. With state-of-the-art superconducting magnets the trap depths of both the ALPHA and ATRAP experiments are about 1 T. Thus, only antihydrogen with kinetic energy less than 0.76 K or 65 μeV will be trapped. The ambient temperature in the current experiments is between 1 and 8 K.

However, we have currently no means to slow and cool the freshly formed anti-atoms, so that to hold the antihydrogen it must therefore be created inside the magnetic trap at a temperature which will allow it to be trapped. As it turns out, this is where matters start to get difficult. Making the antihydrogen inside the trap means that whatever method is used to form the anti-atoms must be compatible with operation of the neutral trap at full strength whilst holding at least one of the charged constituents (antiprotons or positrons), and allowing the recombination of the two under conditions in which the resulting antihydrogen is cold.

It is well established that magnetic field inhomogeneities in Penning–Malmberg traps can cause plasmas to heat and expand (Gilson & Fajans 2003). ALPHA made further studies of this phenomenon and found that the standard magnetic quadrupole used for all normal-matter neutral traps would severely perturb the clouds of antiprotons and positrons thus precluding the formation of antihydrogen cold enough to be trapped (Fajans *et al.* 2005). Instead ALPHA has constructed an octupole (figures 4 and 5), which, for the same field strength at the edge of the trap, has a much lower field in the centre of the trap where the charged particles are held (Bertsche *et al.* 2006). To further avoid influence of the neutral trap fields, ALPHA has implemented and developed techniques to radially compress the electrons, positrons and antiprotons (Andresen *et al.* 2008). Our competitors in ATRAP initially used a quadrupole configuration, but are now constructing an octupole for the 2010 experimental season (G. Gabrielse 2009, personal communication). Recent experiments show that neither the quadrupole nor the octupole fields prevent the formation of *some* antihydrogen (Gabrielse *et al.* 2008; ALPHA 2009, personal communication). However, the temperature of the antihydrogen formed has not yet been measured, and at the time of writing, trapping still eludes both collaborations.

4. Probing antihydrogen

The ultimate goal of both the ALPHA and ATRAP collaborations is the comparison of the transition from the ground state to the first excited state in antihydrogen with that in hydrogen. The upper state that will be addressed is the

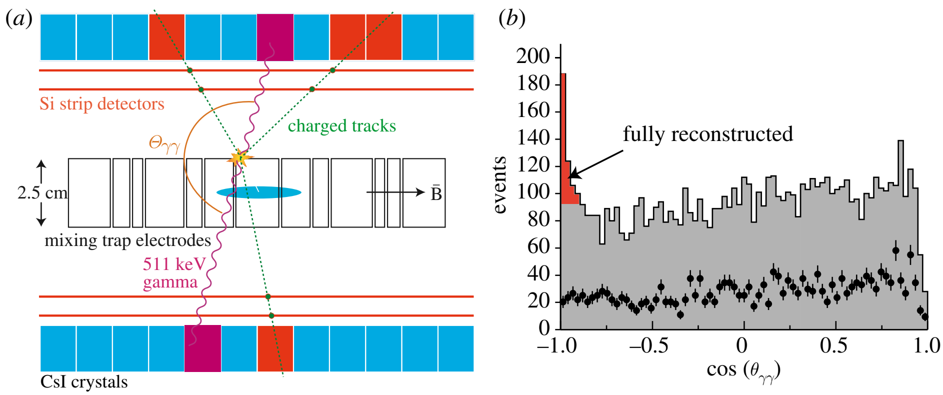

Figure 3. (*a*) Detection of antihydrogen annihilations in ATHENA. When an antihydrogen atom annihilates, two back-to-back photons will emerge from the site together with a number of charged pions (three are shown in the figure). Scintillating CsI crystals (about the size of sugar cubes) detect and measure the energy of the photons and silicon strip detectors resolve the tracks of the pions. Combining the pion tracks, the annihilation vertex of the antiproton can be reconstructed, and time and spatial coincidence with the back-to-back photons can be verified. (*b*) The opening angle of all antiproton annihilation vertices with two time coincident crystal triggers in the first ATHENA antihydrogen measurements. The opening angle of the two crystals as seen from the vertex is 180° if they lie on a line through the vertex. The peak at $\cos(\theta_{\gamma\gamma}) = -1$ in the so-called cold-mixing experiment (grey) therefore shows the first fully detected antihydrogen events. For comparison the plot also shows so-called hot mixing where the positrons were intentionally heated to suppress antihydrogen formation (black circle).

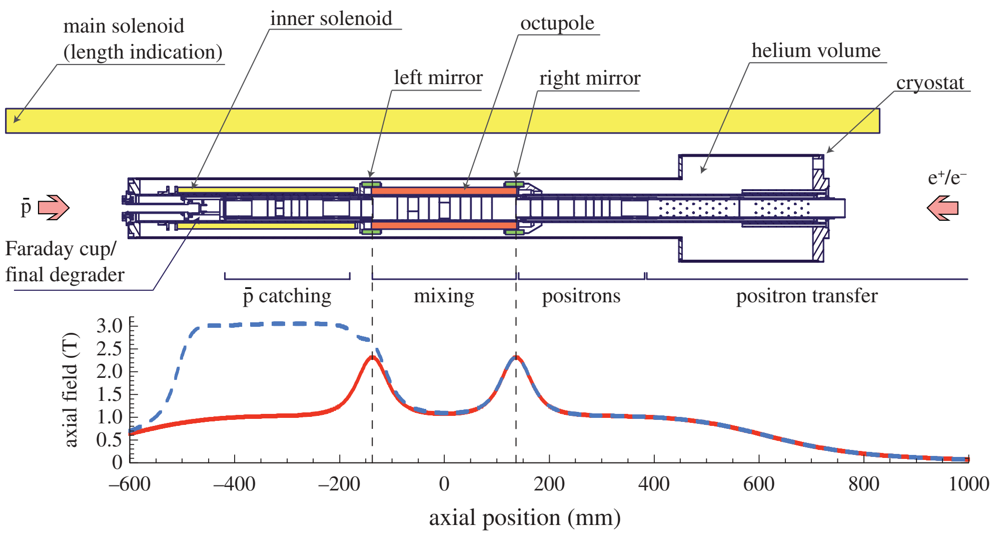

Figure 4. A vertical cut through the ALPHA experimental setup designed to trap antihydrogen. The trap electrodes are shown along the centre of the apparatus. The bottom graph shows the axial magnetic field along the axis of the apparatus. A large external solenoid (not shown) supplies a 1 T axial field throughout. The inner solenoid on the left of the apparatus can raise the general 1 T bias axial field formed by up to 2 T in order to increase the efficiency in trapping antiprotons (which enter from the left). Also visible on the graph is the axial magnetic minimum generated at the zero position (full red line) by powering the mirror coils of the neutral trap.

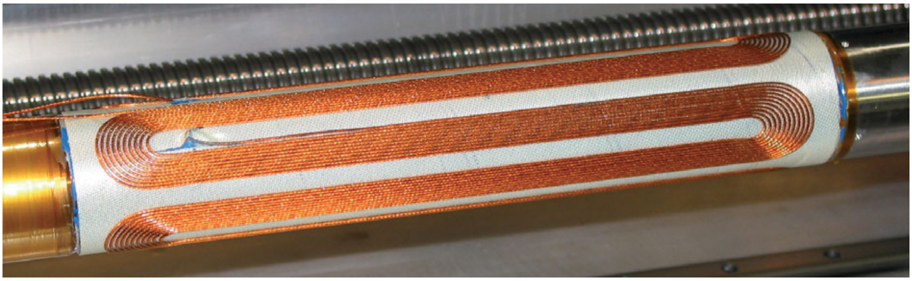

Figure 5. The ALPHA superconducting octupole being wound. The wire is about 1 mm thick and when fully powered holds a current of about 1000 A.

2s state, which has the same angular momentum as the ground (1s) state such that a single photon cannot induce this transition. This causes the upper state to be very long lived (122 ms), and therefore the energy difference between the two states is very well defined.[2] This is therefore an ideal candidate for detailed measurements. Furthermore, this transition has been probed in both trapped hydrogen atoms (Cesar *et al.* 1996) and in a beam (Niering *et al.* 2000), with the latter achieving a precision of about one part in 10^{14}.

There are of course a number of other transitions in antihydrogen which are worth investigating, as different transitions depend in different ways on the interactions of the constituents, and therefore probe different facets of CPT symmetry. Some of these are likely to be carried out before the precision laser spectroscopy detailed above and one particular measurement deserves a few extra lines.

As was discussed in §1 antimatter is a child of quantum field theory. We do not, however, have a quantum version of Einstein's general theory of relativity which describes how the curving of space–time gives rise to the 'illusion' of gravity. What Einstein's theory essentially says is that space–time curves proportionally to the local energy density (or rather the energy-momentum tensor). Matter is very energy-rich (recall the famous equation), thus it curves space. Antimatter is equally energy-rich. We therefore speculate that antimatter will curve space in the same way as matter. This, however, has never been tested, so we do not know how antimatter will behave in space–time curved by matter. Testing this is a test of the weak equivalence principle which states that all bodies, irrespective of their composition, fall at the same rate in a gravitational field.

Measuring the gravitational field on single atoms is difficult as gravity is very weak, and only one experiment (Kellerbauer *et al.* 2008) is actively pursuing this goal for antihydrogen. To illustrate the difficulty think of a trapped cloud of 1 K antihydrogen atoms. The characteristic speed of these anti-atoms is approximately $130\,\mathrm{m\,s^{-1}}$. We can release the cloud and observe the falling antihydrogen. However, over a distance of say 1 m, gravity will only accelerate the particles by $4.4\,\mathrm{m\,s^{-1}}$, which is much less than the spread of velocities in the original sample, and thus difficult to detect.

[2] An uncertainty relation, reminiscent of Heisenberg's, illustrates this well; a long lifetime (meaning we do not know well when the state decays) means a well-defined energy. One could also say that a long lifetime allows for more time to measure the energy.

5. Conclusions and outlook

The creation of the first low energy antihydrogen atoms in 2002 has spurred a massive increase in the interest in antimatter physics and the race is now on to try to trap the anti-atoms and compare them with their matter counterparts. This research is challenging, as the temperature of the antihydrogen formed must be much lower than in the original experiments in 2002 in order for it to be magnetically trapped. Further complications arise from the fact that no appropriate way seems to exist to slow and cool the atoms to aid in trapping, such that the experimenters are forced to make the atoms inside the neutral trap. This feat has only recently been accomplished.

However, in spite of the difficulties, the physics payoff of a successful comparison of hydrogen and antihydrogen can be very large indeed. If any difference is found between the properties of these two the call is out to reformulate quantum field theory, one of the most successful theories of the twentieth century and the foundation of much of modern physics.

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AUTHOR PROFILE

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Dr Niels Madsen is a senior lecturer at the Department of Physics, Swansea University. He received his PhD in physics on laser-cooling of ion beams in 1998 from the University of Aarhus, Denmark. Subsequently, he was awarded a CERN fellowship to work on the commissioning of the Antiproton Decelerator at CERN in Geneva, Switzerland. Once the AD was operational in 2001, a post doc. position at the university of Zürich-Irchel allowed him to work on antihydrogen formation as part of the ATHENA collaboration, who were the first to make low-energy antihydrogen in 2002. In 2003, he was awarded a Steno Fellowship by the National Danish Research Council (then called SNF) to work towards making antihydrogen cold enough to trap. During his fellowship he helped to start the ALPHA collaboration, which is a continuation of the successful ATHENA work. ALPHA aims to trap antihydrogen and perform precision comparisons with hydrogen. He took up his current position in Swansea at the end of 2005.