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Towards trapped antihydrogen

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Abstract

Substantial progress has been made in the last few years in the nascent field of antihydrogen physics. The next big step forward is expected to be the trapping of the formed antihydrogen atoms using a magnetic multipole trap. ALPHA is a new international project that started to take data in 2006 at CERN's Antiproton Decelerator facility. The primary goal of ALPHA is stable trapping of cold antihydrogen atoms to facilitate measurements of its properties. We discuss the status of the ALPHA project and the prospects for antihydrogen trapping.

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1. Introduction

Cold antihydrogen was first produced in 2002 by ATHENA [1] at the Antiproton Decelerator (AD) at CERN [2]. The antimatter atoms were made by letting antiprotons and positrons come into close proximity in a nested Penning trap [3]. After formation the antihydrogen was no longer bound by the electric and magnetic fields of the trap regions and the anti-atoms drifted out to the electrode wall where they annihilated. This actually formed the basis of the detection in ATHENA where a purpose built annihilation detector monitored the tell-tale signs of an antiproton and a positron annihilating at the same time and in the same position [4]. The ATRAP experiment later made similar observations based on an indirect detection

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method of observing antiprotons from re-ionized antihydrogen [5].

Rapid progress has been made in the emerging field over the last few years (see [6,7] for recent reviews). However, in order to attain the precision tests of the CPT theorem and gravity that are the ultimate goals of the field, it will most likely be necessary to trap the formed antihydrogen. The ALPHA experiment has constructed the first apparatus to try to achieve the stable trapping of antihydrogen. In this paper we will describe the apparatus and some of the design considerations that went into it.

2. The alpha apparatus

The ALPHA apparatus has been designed to trap neutral antihydrogen atoms. A schematic overview of the apparatus can be seen in Fig. 1. It consists of an ATHENA-type Penning–Malmberg charged particle trap with a superimposed magnetic trap for the neutral anti-atoms. The apparatus was designed from scratch in a very short time except for the positron accumulator, which was inherited from ATHENA [8].

Neutral atoms, or anti-atoms, can be trapped by interactions between an inhomogeneous magnetic field and their magnetic dipole moment. A trapping potential can then be established by using a minimum-B configuration, as described by Pritchard [9]. In a Ioffe–Pritchard trap the trapping in the radial directions is achieved by a quadrupolar magnetic field, while the trapping in the axial direction is provided by two mirror coils. This trap will be superimposed on the Penning–Malmberg trap for the charge particle constituents in the antihydrogen formation region. Any antihydrogen atom created in a low-field seeking state inside the neutral trap volume with low enough kinetic energy compared to the potential energy due to their magnetic moment would then be trapped magnetically. The trapping depth for ground state antihydrogen is given by

$$U = 0.67\,K/T * \Delta B, \quad (1)$$

where ΔB is the difference between the minimum and maximum fields. Since present superconductor technology does not permit a trap depth of more than a few Tesla this means that the antihydrogen should have kinetic energies in the range of up to 1 K in order to be trapped. Note that this is only valid for the ground state, as excited states would have higher magnetic moments and are thus easier to trap.

The trapping field ΔB in the axial direction in (1) is given by $\Delta B_z = B_m$, where B_m is the strength of the mirror field. In the radial direction ΔB is given by

$$\Delta B = \sqrt{B_s^2 + B_r^2} - B_s, \quad (2)$$

where B_s is the field strength of the solenoid used for charge particle trapping and B_r is the radial field strength of the neutral trap. It follows immediately from (2) that it is useful to employ as small a solenoid field B_s as possible to maximize the trapping depth. However, there are several considerations in determining the optimum solenoidal field for a trapping experiment such as ALPHA. The first one is illustrated by Fig. 2 which shows that the trapping efficiency for antiprotons depends strongly on the solenoidal field in the capture trap and decreases by about an order of magnitude when the field is reduced from 3 T to 1 T. Other considerations are the lifetime and synchrotron cooling times of electrons and positrons in the field which is proportional to B_s^2. To overcome this dilemma ALPHA has opted for a two-solenoid solution with an outer solenoid providing 1 T in the trapping region and another internal solenoid boosting the field in the antiproton capture region to 3 T (see Fig. 1) [10]. Thus we will maintain 3 T in the capture region for better catching efficiency while

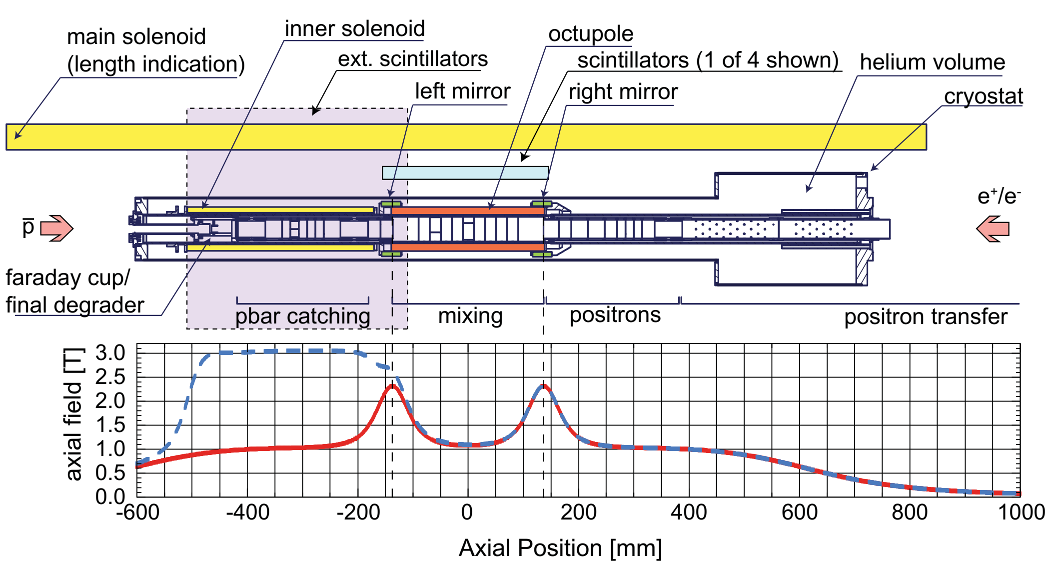

Fig. 1. Schematic view of the ALPHA antihydrogen trap. The graph shows the longitudinal magnetic field on axis due to the solenoids and mirror coils. The *dashed curve* is the field with the inner solenoid energized, whilst the solid line is that without.

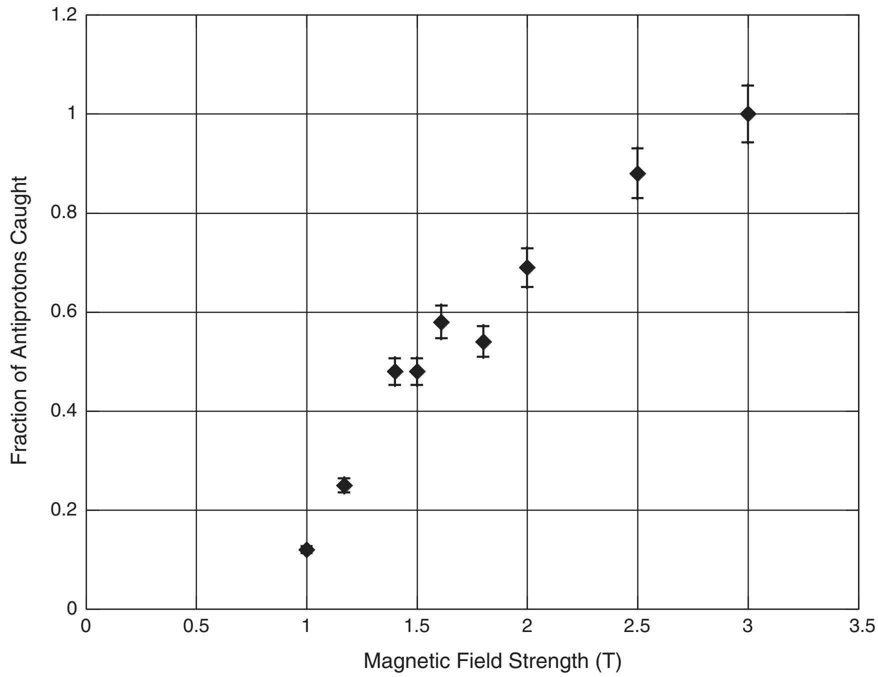

Fig. 2. Results for antiproton trapping efficiency versus magnetic field strength. The measurements are normalized to the value for 3 T field. A relative error of 6% is assumed for all the data points to represent the shot-to-shot variations of the measurements.

providing a low axial field in the formation region to facilitate maximum trapping depth for the neutral atoms.

Traditionally the radial field in a magnetic neutral trap has been provided by a quadrupole magnet. However, recent results have suggested that such fields seriously deteriorate the lifetime of the plasmas in the Penning–Malmberg trap due to the non-homogeneous nature of the magnetic field configuration [11]. This could constitute a major problem as we obviously need to be able to hold on to the charged particle constituents for a long enough time to form antihydrogen. In order to overcome this problem ALPHA has opted to use a higher-order-multipole magnet, or more specifically an octupole configuration instead of the traditional quadrupole radial field [10]. Fig. 3 shows a comparison of the radial field profiles for the ideal quadrupole and octupole configurations and illustrates how the non-uniform field perturbation near the axis, where the charged particles are stored initially, is much smaller for the octupole case. Having decided on an octupole magnet for the neutral trap, Fig. 3 also illustrates some of the wider implications this has for the overall design. While the quadrupole field decreases linearly from the wall to the center, the octupole field decreases much faster near the wall. This means that to be able to use as much of the field for trapping as possible the electrodes need to be very thin and very close to the wall or a large part of the field for trapping the neutrals will be lost. ALPHA has therefore developed new designs for the electrodes used in this region to reduce the total radial width of the electrodes down to 1.2 mm from the wall. In total the ALPHA neutral trap can produce an effective trap depth of 1.18 T corresponding to, from Eq. (1), $U = 0.8$ K for ground state antihydrogen.

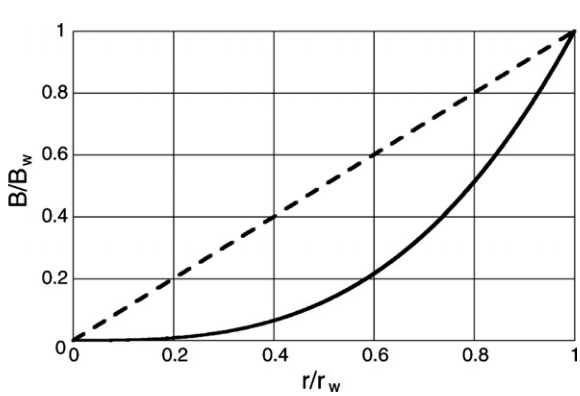

Fig. 3. Ideal radial profiles of the magnetic field for quadrupole (dashed line) and octupole (solid line) coil configurations. B_w is the field at the inner wall of the Penning trap electrode, of radius r_w.

In ATHENA a purpose-built imaging detector was used as the main detector for identifying antihydrogen annihilations. This consisted of two layers of double-sided silicon strips for detecting the annihilation product from antiprotons. Surrounding this were 192 small CsI crystals used to detect the gammas from annihilating positrons [4]. ALPHA is constructing a similar imaging detector. Thus, antiproton annihilation events will be imaged by reconstructing the trajectories of the charged particles (mostly pions) produced in the annihilation of antiprotons using silicon strip detectors. The neutral trap does, however, impose much more stringent conditions than was the case in ATHENA. In order to achieve the maximum trapping depth in the neutral trap it is necessary that the octupole magnet be as close as possible to the trap electrode wall. Hence the detector must be outside the octupole magnet and its cryostat. Having this extra mass inside the detector volume will lead to more multiple scattering events, thus decreasing the spatial resolution of the detector, while the increase in the distance between the annihilation point and the first layer of the detector will further reduce the resolution. This decrease in resolution is countered by having a sufficiently fine pitch in the silicon strip detectors and adding an extra layer of silicon. The total area of the ALPHA detector will also be significantly larger than in ATHENA due to the larger size of the ALPHA traps, which are about a factor of two larger in radius. The gamma detectors have been left out of the ALPHA design due to space considerations and the low efficiency of these detectors (15–20%) and, importantly, because results from ATHENA showed that it was possible to identify antihydrogen annihilations from the spatial distribution of the antiproton annihilations observed using the silicon strips [4].

Beyond the main detector ALPHA has a very wide range of detectors and other diagnostic tools at its disposal. These range from a silicon beam counter measuring the arrival time and position as well as approximate transverse size of the arriving antiprotons, HPDs (hybrid photodiodes) for verifying the number of arriving antiprotons, PMT-based scintillators surrounding the experiment and APD (avalanche photodiode)-based scintillators inside the bore of the main magnet observing individual antiproton annihilations. Positron losses are being monitored by several strategically placed CsI photodiode detectors both outside and inside the bore of the magnet. The number of charged particles can be measured destructively using a calibrated Faraday cup or the plasma size imaged using an MCP/phosphor screen arrangement. A non-destructive plasma modes detection system similar to that used in ATHENA [12] is under development.

3. Recent results

During the short run period from September to November 2006 the ALPHA apparatus was commissioned, apart from the silicon vertex detector. Furthermore, we were able to take the first steps towards cold, trapped antihydrogen.

As mentioned earlier ALPHA decided to opt for an octupole magnet for the neutral trap. One of the first questions to investigate was to try to confirm that the charged particles would survive long enough in the octupole field to allow formation of antihydrogen. Hence we investigated the survival rate of positrons and antiprotons in the multipole field [13]. In Fig. 4 the results for both antiprotons and positrons are shown. We did not observe the rapid loss (ballistic loss) observed in [11] for quadrupole fields and associated with the particles following the field lines of the multipole magnet directly out to the wall. Indeed we observed lifetimes for both species of well above 100 s which is more than sufficient for antihydrogen formation. The ballistic loss and thus the lifetime depend strongly on the radii and length of the plasmas. Although the radii here were unknown the antiprotons were captured at 3 T and subsequently transferred to 1 T, which should cause the cloud to expand by a factor of $\sqrt{3}$. The results show that the magnetic fields of the neutral trap are compatible with the standard mixing scheme using a nested Penning–Malmberg trap.

Another cause for concern was whether it would be possible to produce antihydrogen at the reduced magnetic field of 1 T in the formation region necessitated by the neutral trap. To our knowledge no one has ever previously made cold antihydrogen at fields lower than 3 T. The challenge here is that the charged particle clouds will expand in the low-field as described above. Since the formation process is believed to be three-body recombination (see e.g. [4]) the formation rate should be proportional to n^2, where n is the density of the positron plasma. Thus, the change in magnetic field alone should lead to a decrease in the formation rate of a factor of 3. Furthermore, the synchrotron cooling rate of electrons and positrons should be proportional to the magnetic field, B^2, such that the positron cooling of antiprotons that was observed to precede antihydrogen formation in ATHENA [14] would proceed almost an order of magnitude more slowly at 1 T.

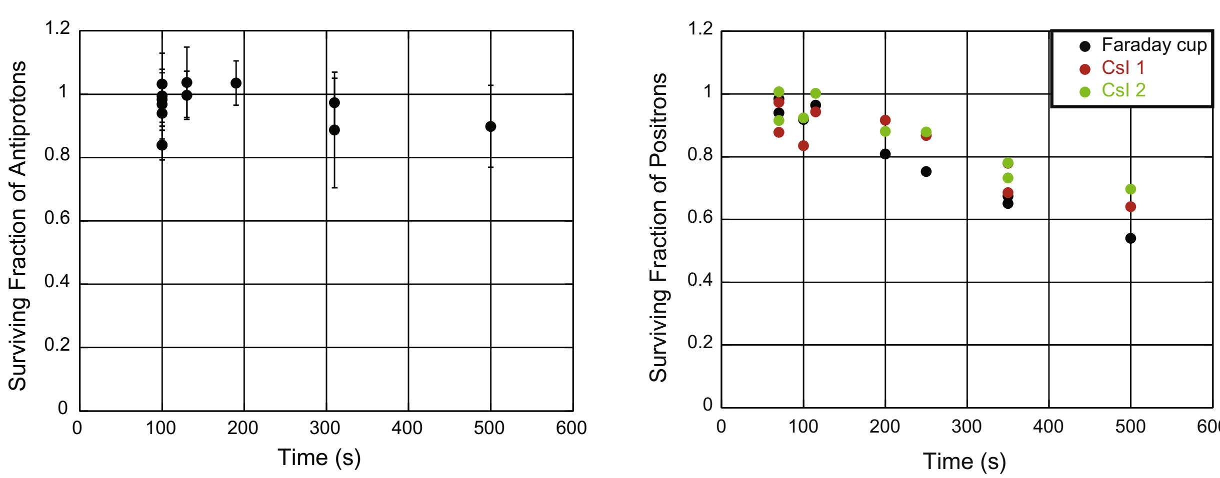

Fig. 4. The ratio of the number of antiprotons (positrons) stored in the octupole field to the number stored without the field is plotted versus holding time.

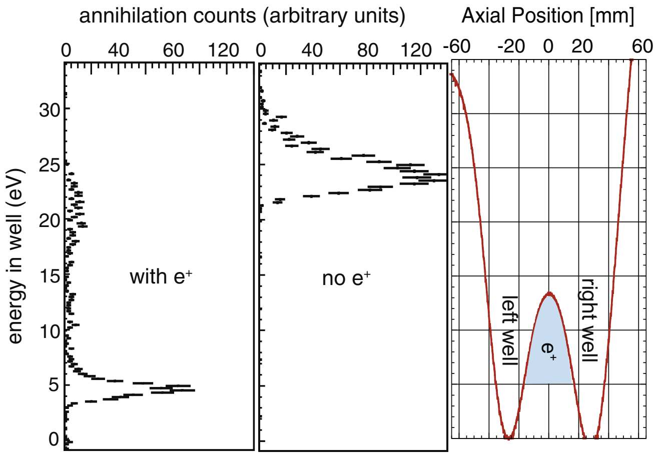

Fig. 5. Antiproton cooling by positrons in a magnetic field of 1 T, making it likely that antihydrogen will form. The figure shows the triggers from the APD scintillators placed inside the bore of the main magnet. These completely surround the trap with a solid angle near unity. The time is measured from the time the antiprotons are injected into the positron plasma.

Our results [15] shown in Fig. 5 indicate that the antiprotons were cooled efficiently at 1 T, even if over a longer period than observed in ATHENA. The efficient cooling of antiprotons in the presence of positrons and the presence of trigger signals from antiproton annihilation with a similar time structure as observed elsewhere for with antihydrogen formation [16], together with the absence of both signals if the positron plasma is either heated to several thousand K or not present during the measurements, leads us to believe that we have most likely been able to make antihydrogen at this lower magnetic field. Since the main ALPHA imaging detector was not yet ready in 2006 we were not able to unambiguously ascertain that we have indeed made antihydrogen, but the results gives us great confidence that we can put this problem behind us.

4. Outlook

In order to achieve antihydrogen that is cold enough to trap in the weak trapping field of a neutral trap, we plan to investigate several variations of the standard nested-trap scheme. This is because results from ATHENA [17] and ATRAP [18] have shown that the standard method mostly produces antihydrogen with a much higher kinetic energy (or temperature) than can be trapped in a neutral trap. This could potentially make it impossible to trap antihydrogen made under such a scheme. The problem is basically that the antiprotons form antihydrogen before they are in complete thermal equilibrium with the positron plasma [17]. The general trends of the variations to the scheme are therefore to try to keep the antiprotons as cold as possible at the time they recombine with a positron to make antihydrogen. This is because the antiproton, by virtue of its larger mass, contributes virtually all the kinetic energy of the newly formed antihydrogen atom. Such variations include e.g. inverted mixing, where the antiprotons are kept stationary in the middle and the positrons are injected into them, or slowly moving the positron plasma into contact with the stationary antiprotons. Other possibilities include forming positronium, the bound state of an electron and a positron, somewhere nearby to facilitate interaction with the antiprotons. Only further tests will show which one of these formation methods hold the most promise for creating large numbers of antihydrogen cold enough to trap.

Another area under investigation is compression of the charged constituent plasmas using the rotating wall technique [19,20]. This is because the size of the plasmas influences their survival in the multipole field, as described above, with well-centered plasmas suffering fewer losses. Better control of the plasma size should also promote more complete overlap of the two plasmas, which again should lead to better control over the formation process and possible higher rates of formation.

5. Summary

We have presented the ALPHA antihydrogen apparatus. We have shown that antiprotons and positrons can survive the magnetic fields of an octupole neutral trap sufficiently long to allow them to make antihydrogen. We have further shown that antiprotons can be captured at high magnetic field and transferred to a lower field without significant losses and that they can subsequently make antihydrogen in this low-field environment without further manipulations. This lower field will make it possible to erect a neutral trap with significantly higher well depth than would be possible at higher solenoid fields. These advances prepare the way for attempts to trap antihydrogen.

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