Antimatter Plasmas in a Multipole Trap for Antihydrogen

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We have demonstrated storage of plasmas of the charged constituents of the antihydrogen atom, antiprotons and positrons, in a Penning trap surrounded by a minimum-B magnetic trap designed for holding neutral antiatoms. The neutral trap comprises a superconducting octupole and two superconducting, solenoidal mirror coils. We have measured the storage lifetimes of antiproton and positron plasmas in the combined Penning-neutral trap, and compared these to lifetimes without the neutral trap fields. The magnetic well depth was 0.6 T, deep enough to trap ground state antihydrogen atoms of up to about 0.4 K in temperature. We have demonstrated that both particle species can be stored for times long enough to permit antihydrogen production and trapping studies.

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Antihydrogen atoms are of fundamental interest due to the potential of performing sensitive tests of *CPT* symmetry based on comparison of the spectra of hydrogen and antihydrogen. Following the initial synthesis of cold antihydrogen [1] by the ATHENA collaboration at the CERN Antiproton Decelerator (AD) [2] in 2002 and the similar result [3] by the ATRAP collaboration, the experimental effort in this emerging field has focused on understanding antihydrogen production mechanisms and dynamics [4–9] and investigating new production schemes [10,11].

In the previously cited experiments, the neutral antiatoms, which are produced in Penning traps from cold plasmas of positrons and antiprotons, escaped the production volume, either to annihilate or to be field ionized. For future laser experiments on antihydrogen, it is very desirable, and possibly necessary, to be able to trap and hold the neutral antiatoms. For example, the 1S-2S transition in hydrogen, often cited as an ideal spectral line for a *CPT* comparison, has an excited state lifetime of about 1/8 of a second. The antihydrogen atoms produced in ATHENA annihilated on the walls of the apparatus on the order of 10 μs after formation.

Antihydrogen atoms can in principle be trapped through the interaction of their magnetic dipole moments with an inhomogeneous magnetic field. The prototypical field configuration, developed for trapping hydrogen atoms, is the Ioffe-Pritchard geometry [12], featuring a transverse quadrupole winding and longitudinal mirror coils. These produce a minimum in the magnetic field strength at the trap center, so that weak-field seeking quantum states can be confined. The trap depth is given simply by

$$U = \mu \Delta B, \tag{1}$$

where μ is the magnetic dipole moment and ΔB is the difference between the maximum and minimum field strengths in the device. It is customary to quote this trap depth in temperature units. For ground state antihydrogen the relevant number is about 0.7 K per Tesla of ΔB, underlining the need for *cold* antihydrogen production. Assuming antihydrogen can eventually be produced at

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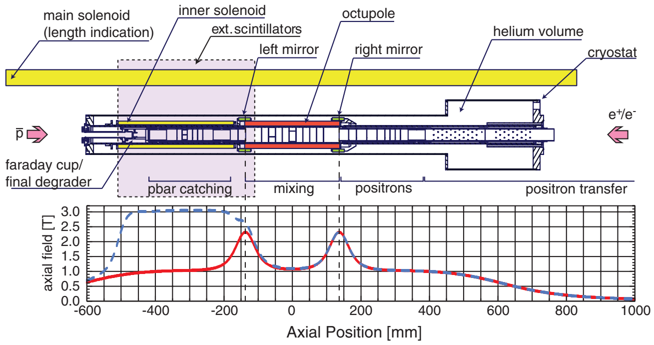

FIG. 1 (color). Schematic diagram of the ALPHA apparatus. The graph shows the on-axis longitudinal magnetic field due to the solenoids and mirror coils. The blue (red) curve is the field with (without) the inner solenoid. The positron accumulator (not pictured) is located to the right of the apparatus.

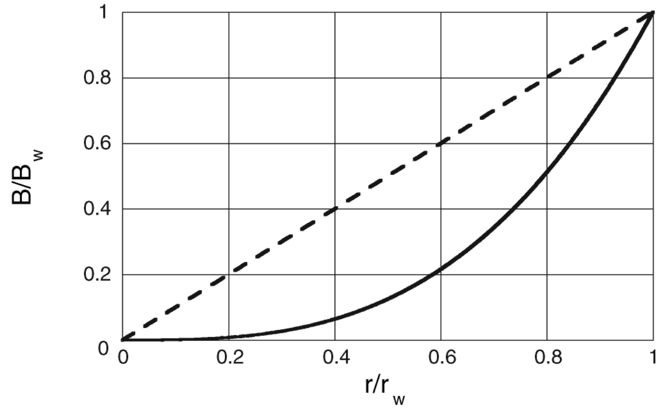

FIG. 2. Magnetic field strength versus radius for an ideal quadrupole (dashed line) and an ideal octupole (solid line). B_w is the field at the inner wall (radius r_w) of the Penning trap.

4 K, this number also sets the scale for the size of the magnetic fields necessary for trapping even a fraction of the antiatoms. Note, however, that highly excited antihydrogen atoms, as produced in ATHENA and ATRAP, may have significantly higher magnetic moments. The decay of such excited states in a neutral trap is a subject of current theoretical study [13].

In order to pursue the long-term goal of performing spectroscopy on antihydrogen, we have constructed a new apparatus, called ALPHA (antihydrogen laser physics apparatus), that combines an antihydrogen production Penning trap with a neutral antiatom trap [14]. The strategy behind this device is to mix cold plasmas of antiprotons and positrons near the minimum of magnetic field strength in the combined trap, so that antiatoms can be "born" trapped, if their kinetic energy does not exceed the effective neutral trap depth. Figure 1 is a schematic view of the apparatus.

An important consideration for such a device, and a subject of some debate in the field [15,16], is the effect of the magnetic fields of the neutral trap on the charged particle plasmas used to synthesize antihydrogen. Penning trap plasmas depend on the azimuthal symmetry of the solenoidal field for their stability [17]. Earlier work by some of us [18] indicates that quadrupole fields, as used for trapping hydrogen, are not suited for our application, because, for realistic trap depths, the quadrupole field leads to rapid loss of the charged particles. ALPHA features a novel, superconducting neutral atom trap comprising a transverse octupole and longitudinal mirror coils [14]. The octupole was chosen to minimize perturbations on the trapped constituent plasmas due to the azimuthally asymmetric magnetic fields. As illustrated in Fig. 2, for equivalent well depths, an octupole has a significantly lower field near the trap axis, where the charged particle plasmas are initially stored. A higher-order multipole would even further reduce the perturbation, but practical considerations involving fabrication of the magnet make an octupole the best choice for our application [14]. Compared to a quadrupole of equal strength, the octupole field results in a lower radial trapping frequency for antihydrogen. This may be a concern for future laser experiments and could be addressed, in a next-generation device, by adding a quadrupole that is energized *after* trapping of the neutrals.

In such a combined Penning-neutral atom trap, the solenoidal Penning field defines the "bottom" of the potential well for the neutral atoms. The "top" of the trap is determined by the field strength at the inner radius of the Penning trap electrodes (transversely) and at the z position of the peaks of the mirror coil field (longitudinally). Transversely, the relevant ΔB is

$$\Delta B = \sqrt{B_s^2 + B_w^2} - B_s, \tag{2}$$

where B_s is the solenoid field strength, and B_w is the transverse field strength of the multipole at the inner wall of the Penning trap.

There is thus a conflict between the need for a high solenoid field to maximize antiproton capture from the AD and the desire for a low solenoid field to maximize the achievable neutral well depth. To satisfy both criteria, ALPHA employs an innovative two-solenoid approach to producing the longitudinal field for the Penning traps. The outer solenoid, spanning the entire experiment, is held at 1 T, while the inner solenoid, which covers only the antiproton catching region, provides an additional 2 T. Thus antiprotons can be captured at 3 T (as in the ATHENA experiment) and then transferred to a lower field (1 T) for mixing with positrons, in the combined trap; see the field plot in Fig. 1.

There are three distinct trapping regions in the ALPHA apparatus: one for catching and cooling antiprotons, one for catching and manipulating positrons from the accumulator, and one for mixing antiprotons and positrons to form antihydrogen. All charged particle traps are cooled to 4 K by the same liquid helium cryostat used to cool the inner superconducting magnets.

Results for positron storage times in the ALPHA device are depicted in Fig. 3. Positrons were accumulated for 300 s in the same Surko-type device [19,20] used successfully in the ATHENA experiment. The positrons were then transferred at 52 eV from the positron accumulator into a Penning trap in the 1 T longitudinal field in the mixing region. The particles were held in a two-electrode trap (each electrode is 20 mm in length) having an on-axis depth of 49 eV, parameters similar to those of the center well of our nested trap for antihydrogen mixing. After being dynamically trapped, the positrons were allowed to cool by emission of cyclotron radiation for about 30 s. The octupole was then ramped to 700 A, which produces 1.2 T at the inner wall (radius 22.3 mm) of the Penning trap. The octupole current was ramped at 20 $A\,s^{-1}$, held constant for varying times, and then ramped down at the same rate. At the end of the ramp, the particles were ejected onto a Faraday cup to measure the remaining charge. A hold time of 100 s in the graph thus corresponds to 30 s of octupole field flattop. Two CsI detectors measured annihilation gamma rays from the positrons hitting the Faraday cup to provide an independent check of the relative number. The number of positrons injected was typically 3×10^7, with shot-to-shot variations of about 10%. Measurement cycles with the octupole were alternated with identical, but octupole-free, cycles to determine the fractional survival rate of particles in the combined field. Each data point is the average of at least three identical pairs of field-on or field-off measurements. Within the shot-to-shot variations, we observed no loss of positrons without the octupole field, even at the longest times measured here.

Similar measurements were performed on antiprotons. Antiprotons from the AD (5.3 MeV) were slowed in a foil (degrader in Fig. 1), trapped using a pulsed electric field, and electron cooled in the antiproton catching trap, a 5 keV deep Penning trap immersed in the 3 T field region. A single AD shot of about 2×10^7 particles yields several thousand cold antiprotons for further manipulation. After an electron cooling time of 30 s, the electrons were ejected from the trap and the antiprotons transferred into the 1 T mixing region. This transfer was accomplished with less than 10% particle loss, confirming one key design feature of the ALPHA device. (All previous antihydrogen experiments were performed in a longitudinally uniform solenoidal field.) The antiprotons were held in a single electrode trap (electrode length 20 mm) having an on-axis depth of 43 eV. The measurement cycle was identical to that for positrons, except that the relative antiproton number was determined by using scintillators to detect particle annihilation when they impact the Faraday cup. The results are depicted in Fig. 4. Taken together, the antiproton and positron manipulations described above should simulate the situation immediately before particle mixing in an antihydrogen synthesis or trapping cycle.

The results for survival of both particle types in the combined trap are striking in that little or no loss is observed on time scales relevant for antihydrogen production experiments. In ATHENA, antihydrogen was produced and detected for only a few tens of seconds after the start of particle mixing [6]. Positron losses at the longest time measured here never exceeded 40%, and the antiproton losses are even smaller.

Two types of possible particle loss were anticipated due to the perturbations of the multipole field. The first is an essentially immediate loss that results if a particle simply follows a field line that leads it to the Penning trap wall [18]. For a given plasma length and octupole field strength, the octupole field essentially imposes a maximum radius on the plasma, above which loss is immediate. The maxi-

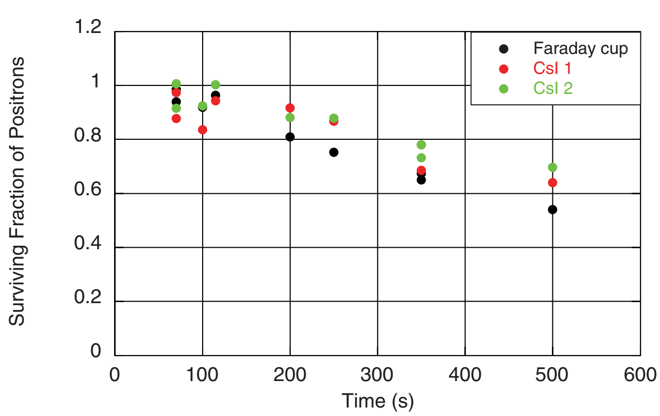

FIG. 3 (color). The ratio of the number of positrons stored in the octupole field to the number stored without the field is plotted versus holding time, as measured with a Faraday cup and with two CsI detectors. Error bars (typically ±10%) omitted for clarity. See text for explanation of the measurement cycle.

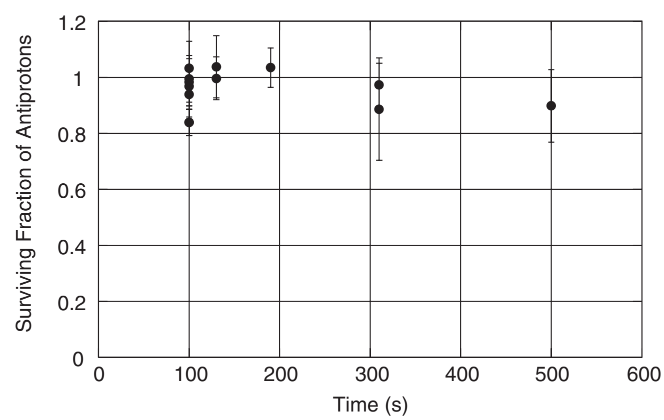

FIG. 4. The ratio of the number of antiprotons stored in the octupole field to the number stored without the field is plotted versus holding time. Error bars are standard deviations for one set of measurements. Repeated measurements illustrate run-to-run variations. See text for explanation of the measurement cycle.

mum radius decreases as the plasma length increases. This so-called ballistic loss should be much reduced for an octupole as compared to a quadrupole [21,22], but this is the first experiment to attempt to observe this effect with antimatter plasmas. Our data indicate that this loss is not significant for the plasmas studied here, since we see no more than 10% loss at the shortest time scale. Note, however, that this loss could still be significant for longer and/or larger radius plasmas, so that it may be an issue for antiprotons injected into a longer nested Penning trap as used in ATHENA. We can, however, conclude that static positron plasmas as used in ATHENA and ALPHA can easily survive the imposed multipole field. Further measurements are necessary to determine if there is a significant positron plasma density decrease after imposition of the multipole field.

A second mechanism, diffusive growth of the plasma due to the cylindrical asymmetry of the magnetic field [23,24], probably accounts for the loss on longer time scales. The fact that positrons seem to suffer more than antiprotons may suggest a collisional contribution to this diffusion, since the positrons are present in much larger numbers and with much higher density. The longer trap length may also play a role. The loss is not worrisome on antihydrogen production time scales, but, as above, there may be a measurable reduction in particle densities due to diffusion. A deleterious effect on particle temperatures can also not be ruled out at this stage.

Compared to the earlier studies with electron plasmas [18], the current work indicates the clear superiority of the octupole configuration over a similar strength quadrupole. A relative figure of merit for comparing different types of multipole traps is the ratio B_w/B_s of the transverse field strength at the Penning trap inner wall to the solenoid field strength. This ratio is about 1.2 for a current of 700 A in the ALPHA octupole. In the cited article the authors studied electron plasmas of similar sizes to the ALPHA positron plasmas. They were unable to store electrons in a quadrupole configuration having B_w/B_s of 1.2.

The current measurements represent a first, encouraging, milestone towards antihydrogen trapping. We have shown that the charged constituent plasmas—trapped and manipulated in an actual antihydrogen device—are quite robust when subjected to an octupole trapping field of a strength necessary to constitute a realistic neutral anti-atom trap. The long storage times indicate that plasma manipulations, such as applying a rotating wall electric field [25] to compress the radius of one plasma or the other, should be possible *in situ* before the start of mixing. This may be important in order to achieve smaller plasma radii, higher particle densities, and thus higher antihydrogen production rates in the 1 T field. The ALPHA mixing trap is configured for this eventuality. In summary, we have established that the ALPHA approach of using a higher-order multipole for the transverse trapping of antihydrogen is compatible with the storage of the constituent plasmas, with numbers comparable to those of earlier antihydrogen experiments.

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