First Capture of Antiprotons in an Ion Trap: Progress Toward a Precision Mass Measurement and Antihydrogen

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First Capture of Antiprotons in an Ion Trap: Progress Toward a Precision Mass Measurement and Antihydrogen

G. Gabrielse, X. Fei, L. Haarsma, S. L. Rolston and R. Tjoelker

Department of Physics, Harvard University, Cambridge, MA 02138, USA

T. A. Trainor

Department of Physics, University of Washington, Seattle, WA 98195, USA

H. Kalinowsky and J. Haas

Institute fur Physik, University of Mainz, West Germany

and

W. Kells

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

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Abstract

Antiprotons from the Low Energy Antiproton Ring of CERN are slowed from 21 MeV to below 3 keV by being passed through 3 mm of material, mostly Be. While still in flight, the kilo-electron volt antiprotons are captured in a Penning trap created by the sudden application of a 3-kV potential. Antiprotons are held for 100 s and more. Prospects are now excellent for much longer trapping times under better vacuum conditions. This demonstrates the feasibility of a greatly improved measurement of the inertial mass of the antiproton and opens the way to other intriguing experiments. The possibility of producing antihydrogen by merging cold, trapped plasmas of positrons and antiprotons is discussed.

1. Introduction

The basis for this discussion is the recent success of our TRAP collaboration in slowing and capturing antiprotons in an ion trap [1]. However, I first discuss the inertial mass of the antiproton since its measurement is our initial motivation for trapping antiprotons (Section 2), before reviewing the slowing and capture of antiprotons (Section 3). After a measurement of the inertial mass, our collaboration is increasingly interested in the production of antihydrogen. It seems that the highest rate may come from a collisional process (Section 4). Other possible collision studies are mentioned. (Section 5).

2. The antiproton mass [2]

Measurements of the antiproton mass [3–6] are represented in Fig. 1. All of these are deduced from measurements of the energy of X-rays radiated from highly excited exotic atoms. For example, if an antiproton is captured in a Pb atom, it can make radiative transitions from its $n = 20$ to $n = 19$ state. The antiproton is still well outside the nucleus in this case, so that nuclear effects are small. The measured transition energy is essentially proportional to the reduced mass of the nucleus and hence the antiproton mass can be deduced by comparing the measured values with theoretical values, corrected for QED effects. The most accurate quoted uncertainty is 5×10^{-5} and is consistent with the much more accurately known proton mass, indicated by the dashed line.

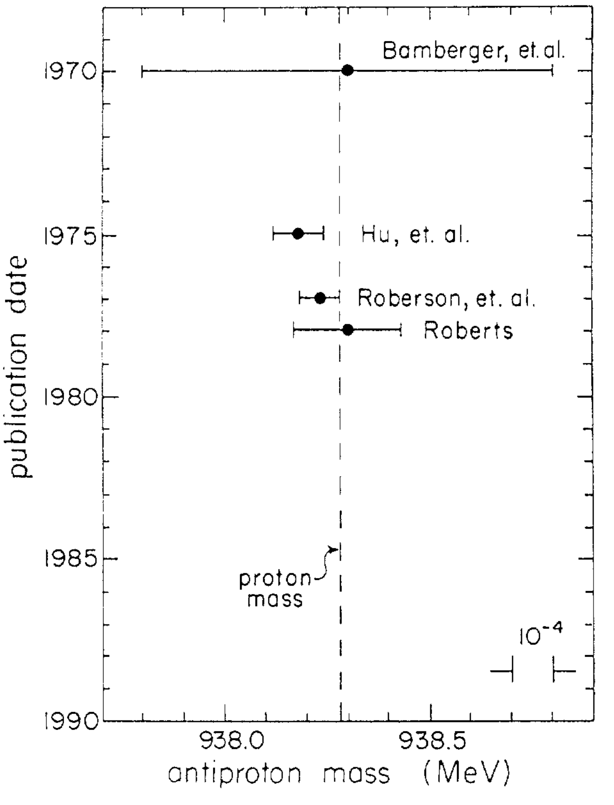

Fig. 1. Antiproton mass measurements.

Since 1978 it has not been possible to extend the accuracy realized with the exotic atom method. Based upon precisions obtained with trapped electrons, positrons and protons, it seems very likely that the measurement uncertainty in the ratio of antiproton to proton masses could be reduced by more than 4 orders of magnitude, to order 10^{-9} or better. A similar accuracy will be sought with a RF spectrometer [7].

Comparison of the antiproton and proton masses is a test of CPT invariance since CPT invariance implies that the inertial masses be the same. The current status of experi-

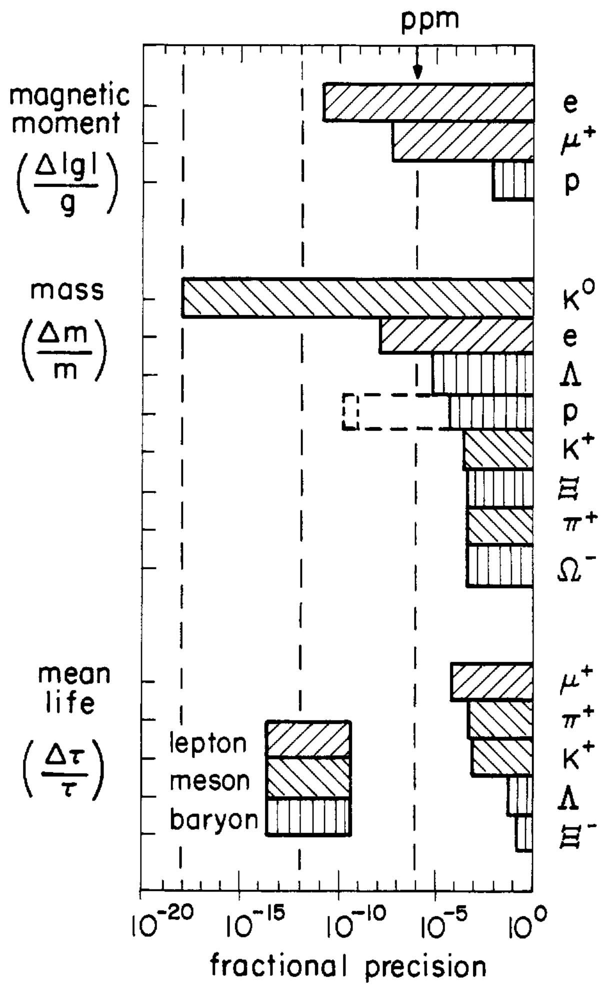

Fig. 2. Tests of CPT.

mental tests of CPT invariance is summarized in the Particle Data Group compilation [8] as indicated in Fig. 2. Since CPT invariance implies that a particle and antiparticle have the same magnetic moment (with opposite sign), the same inertial mass and the same mean life, the tests are so grouped for various baryons, mesons and leptons. The neutral kaon system provides a test of CPT invariance of striking precision. Equally striking, however, is that only 3 other tests exceed 1 part per million in accuracy, and these involve leptons only. In fact, there is not even a single precision test of CPT invariance with baryons. The widespread faith in CPT invariance is clearly based upon the success of field theories in general and not upon a dearth of precision measurements.

It is even conceivable that proton and antiproton masses could be different without a violation of CPT invariance. CPT invariance relates the mass of a proton in a matter universe to an antiproton in an antimatter universe. A long range coupling to baryon number would not affect the kaon system but could shift differently the proton and antiproton masses, given the preponderance of baryons in our apparatus.

The scarcity of precise tests of CPT invariance makes the case for a precise comparison of proton and antiproton masses seem to be very strong to me, especially since no precise test at all involves baryons. Such a measurement also satisfies several additional criteria.

1. A big improvement in accuracy is involved, somewhere between four and five orders of magnitude.
2. A simple, basic system is involved.
3. The technique used will be convincing if the masses are found to differ.
4. The measurement will involve a reasonable effort.
5. It will be fun.

The last two criteria are more subjective than the others, but important nonetheless.

3. First slowing and capture of antiprotons in an ion trap

Antiprotons are created at energies of several GeV. Precision experiments in Penning traps take place at millielectron volts (meV). An experimental difficulty, than, is to reduce the antiprotons kinetic energy by approximately 12 orders of magnitude. The first slowing, from GeV energies down to MeV energies takes place within LEAR. The unique capabilities of this machine are well known, so I will not discuss them further.

I am delighted to report that our TRAP Collaboration (PS196) has taken 21.3 MeV antiprotons from LEAR (200 MeV/c) and slowed them down to below 3 keV. At this energy they were caught in the small volume of an ion trap and held up to ten minutes. I should point out that this effort succeeded despite incredible time pressure. The capture of antiprotons, for example, occured during a single 24 h period. A published account is available [1] so I will only briefly summarize.

The experiments went in two stages. In May 1986, we used a simple time-of-flight apparatus (Fig. 3) to measure the energy distribution of antiprotons emerging from a thick degrader. As degrader thickness is increased, the number of transmitted antiprotons drops as more of them are stopped in the degrader (Fig. 4(a)). The degrader thickness at the half intensity point is very close to the proton range which is compiled in standard tables. Most of these transmitted antiprotons have energies above 3 keV which is the highest energy we could trap. However, we were able to show that the number of antiprotons which emerge from the degrader with low kinetic energies (along the beam axis), between 2 and 8 keV, is clearly peaked at the half intensity point for antiprotons of all energies (Fig. 4(b)). Approximately 1 in 10^4 of the incident antiprotons emerges from the degrader with below 3 keV. These are the particles available for trapping. I should point out here that there is some interest in the collisional slowing within the degrader and that we have measured energy distributions as a function of degrader thickness.

In July 1986 we returned to LEAR for a 24 h attempt to actually catch antiprotons in the small volume of an ion trap. The slowest antiprotons leaving the thick degrader are confined in 2 dimensions to field lines of the 6T superconducting magnet and are so guided through the series of 3 trap electrodes. As the antiprotons enter the trap, a first ring-shaped trap electrode (the entrance endcap) and a main ring electrode are both grounded. A third cylindrical electrode (exit endcap) is at -3 kV so that negative particles with energy less than 3 keV turn around on their magnetic field lines and head back towards the entrance of the trap. Approximately 300 ns later, before the antiprotons can escape through the entrance, the potential of the entrance endcap is suddenly lowered to -3 kV, catching them within the trap. The potential is switched in 15 ns with a kryton circuit developed for this

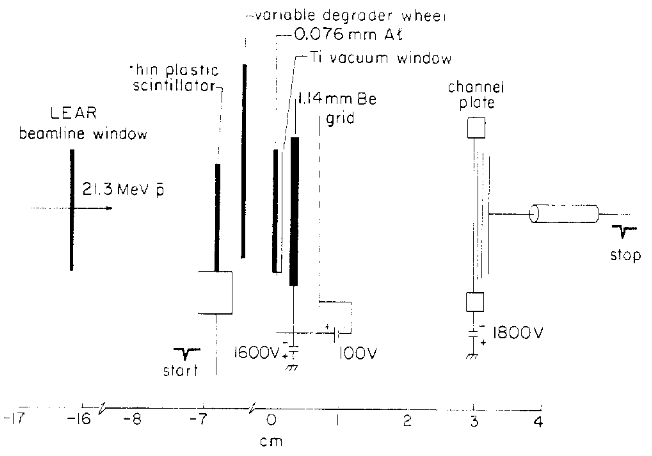

Fig. 3. Time-of-flight spectrometer.

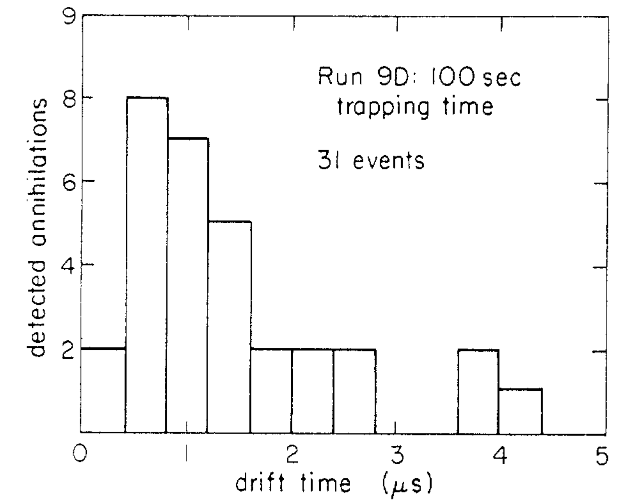

Fig. 5. Time-of-flight spectra.

purpose and is applied to the trap electrodes via an unterminated coaxial transmission line. (9)

After antiprotons are held in the trap between 1 ms and 10 minutes, the potential of the exit endcap is switched from -3 kv to 0 volts in 15 ns, releasing the antiprotons from the trap. The antiprotons leave the trap along respective magnetic field lines and annihilate at a beam stop well beyond the trap. The high energy charged pions which are released are detected in a 1 cm thick cylindrical scintillator outside the vacuum system. A multiscaler started when the potential is switched records the number of detected annihilations over the next 6 μs in time bins of 0.4 μs. A second multiscalar records the pion counts over a wider time range with less resolution to monitor backgrounds.

Fig. 5 shows a time-of-flight spectrum for antiprotons kept in the trap for 100 s. The spectrum includes 31 distinctly counted annihilations which corresponds to 41 trapped particles when the detector efficiency is included. We carefully checked that these counts are not electronic artifacts. When the high voltage on the exit endcap is switched to release antiprotons from the trap, a single count (occasionally two) is observed in the multichannel scalers. We take this to be time $t = 0$ and always remove a single count from the measured spectra. Otherwise, the background is completely negligible. When the potential of the entrance endcap is switched on just 50 ns before 3 keV antiprotons arrive in the trap, when the magnetic field is off, or when the -3 keV on one of the electrodes is adiabatically turned off and then back on during a 100 s trapping time to release trapped antiprotons, no counts are observed.

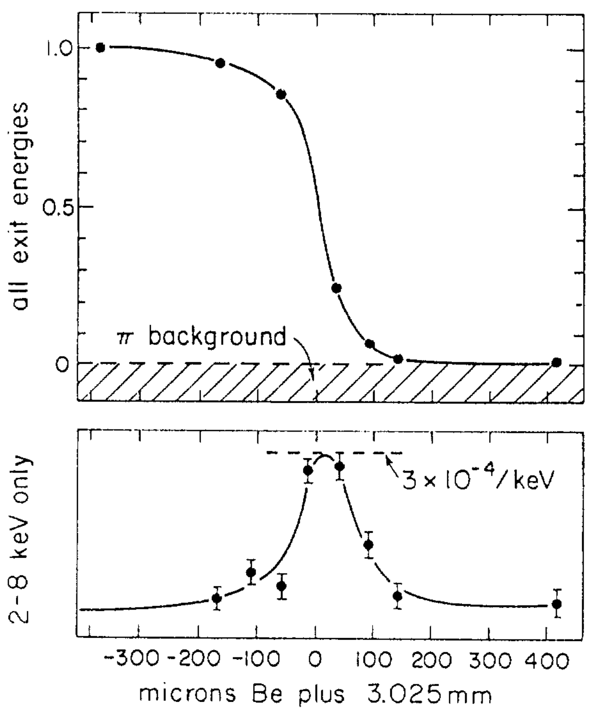

Fig. 4. Transmission of antiprotons as a function of Be thickness for
(a) Antiprotons of all exit energies
(b) Antiprotons with exit energies between 2 and 8 keV.

The potential on the exit endcap is lowered quickly compared to the transit time of particles in the trap in order to maximize the detection efficiency. Even a small number of trapped particles can be observed above possible background rates in the 6 μs window. For trapping times shorter than 100 s, however, we actually released so many trapped antiprotons that our detection channel is severely saturated. The saturation distorts the shape of the time-of-flight spectrum [1]. For a 1 ms trapping time, we conservatively establish that more than 300 antiprotons are trapped out of a burst of 10^8, which corresponds to trapping 3×10^{-6} of the antiprotons incident at 21.3 MeV and 3% of the antiprotons slowed below 3 keV in the degrader. We observe that 5 particles remain in the trap after 10 minutes. This is actually based upon only two trials (since we were reluctant to use up our short time at LEAR holding antiprotons for long times), but both of these trials used a burst of antiprotons from LEAR of comparable intensity to that used for the 41 trapped particles of the 100 s spectra in Fig. 5. If a simple exponential decay describes the number of particles trapped between 100 s and 10 minutes, the decay time is 240 seconds. An extrapolation back to the loading time $t = 0$, however, would then indicate that only 62 particles are initially trapped. We clearly observe many more for a trapping time of 1 ms, suggesting that antiprotons are lost more rapidly at earlier times.

A key point here is that the rate of cooling and annihilation via collisions with background gas will decrease with decreasing pressure. The background pressure can be made lower by orders of magnitude compared to the present vacuum by cooling a completely sealed vacuum enclosure to 4.2 K.

We thus expect a very significant increase in achievable trapping times.

4. Antihydrogen production

Our Trap Collaboration is increasingly interested in the possibility of producing antihydrogen. W. Kells, L. Haarsma, S. L. Rolston and myself are presently preparing a paper which gives more details. We know of 3 proposed methods to make antihydrogen. The first is to merge beams of antiprotons and positrons, moving at the same velocity within a storage ring [10]. The mechanism is radiative recombination,

$$p^- + e^+ \rightarrow \bar{H} + h\nu, \tag{1}$$

the extra energy being carried off by a photon. This process may be stimulated

$$p^- + e^+ + h\nu \rightarrow \bar{H} + h\nu' \tag{2}$$

with a possible increase of 100 in rate for stimulation to $n = 2$ [11]. Nonetheless, the antihydrogen production rate is still very low, less than 1 per second. Radiative recombination is slow because the time required to radiate a photon is typically much larger than the radiative time between antiprotons and positrons.

The second method is to collide positronium with trapped antiprotons [12]

$$p^- + e^+e^- \rightarrow \bar{H} + e^- \tag{3}$$

The cross section is much higher than for radiative recombination since the excess energy is carried off by the electron. However, the positronium e^+e^- is relatively hot (compared to 4.2 K) and hence the large additional enhancement discussed in the following paragraph is not available. Also, positronium is shortlived and neutral so it cannot be kept for a long time in an ion trap until recombination occurs. If we assume 10^4 antiprotons in a trap source, the proposed rate scales to 10^{-3} per second.

We have recently learned that another 3 body process might produce antihydrogen at a much higher rate.

$$p^- + e^+ + e^+ \rightarrow \bar{H} + e^+ \tag{4}$$

The equivalent process with protons, electrons and hydrogen has been studied in some detail [13]. For a plasma of charged antiprotons and positrons at temperature T, this 3 body rate is proportional to the density of antiprotons, the square of the density of the positrons, the interaction volume and to $T^{-9/2}$. At 4.2 K, for 10^4 antiprotons/cm^3, 10^7 positrons/cm^3 and an interaction volume of $1\,\text{cm}^3$, the instantaneous rate for antihydrogen production is 6×10^6/s. The potentially high rate is very encouraging and is being investigated in more theoretical detail, including the consequences of electric and magnetic fields [14].

We intend to begin experimental studies with protons and electrons, to explore the possibility of producing a 4.2 K plasma of antiprotons and positrons in a RF trap [15] or in a nested pair of Penning traps [16]. The first experiment with antiprotons would be to measure the depletion of trapped antiprotons and positrons as they interact, along with the annihilation pions from antihydrogen hitting the walls of the trap. For the future it would be nice and perhaps necessary to capture antihydrogen as it is formed in a surrounding neutral particle trap [2]. We find it very encouraging that since we have been thinking of this difficult scenario, that copious amounts of hydrogen have been confined in a neutral particle trap [17], and that there are now intentions [18, 19] to slow hydrogen and trap it as a means for doing more precise spectroscopy of hydrogen. With trapped and cooled antihydrogen, it would be possible to measure the gravitational acceleration of a neutral antihydrogen atom by observing how the gravitational force shifts the location of an antihydrogen atom in a magnetic trap. Again, we find it encouraging that such effects were recently observed with trapped Na atoms [20].

5. Other possibilities

Other collisional studies can be done with the trapped antiprotons. Rates are likely to be low, however, with only 10^3 antiprotons confined within a trap volume of order $1\,\text{cm}^3$ to $1\,\text{mm}^3$. Because annihilation rates can be detected so efficiently, it may be possible to study the interactions of the trapped antiprotons with various gases introduced into the trap. Protonium (the bound state of a proton and an antiproton) could be formed at very low pressures and the X-rays from its decay could be detected without the Stark shifts associated with protonium formation in dense gases. Finally, it may be possible to completely strip all of the electrons from a rather heavy ion since such stripping has been observed [21]. An antiproton captured by a trapped ion would eject bound electrons as it cascaded down, limited primarily by the amount of energy available for ejecting electrons. Eventually, the antiproton would annihilate with a nucleon, producing various isotopes.

Acknowledgements

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