Cooling and Slowing of Trapped Antiprotons below 100 meV

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Electron cooling of trapped antiprotons allows their storage at energies more than 6×10^7 times lower than is available in any antiproton storage ring. More than 60000 antiprotons with energies from 0 to 3000 eV are stored in an ion trap from a single pulse of 5.9-MeV antiprotons from LEAR. Trapped antiprotons maintain their initial energy distribution over days unless allowed to collide with a cold buffer gas of trapped electrons, whereupon they slow and cool below 100 meV in 10 s. The antiprotons are cooled in a harmonic potential well suited for precision measurements and have remained more than 2 days without detectable particle loss. Energy widths as narrow as 9 meV are directly observed.

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Interesting experiments await the availability of very-low-energy antiprotons. For example, a much more accurate measurement of the inertial mass of the antiproton becomes feasible with antiproton energies below 1 meV.[1] This would be one of only a few precise tests of *CPT* invariance, the only such test with baryons.[2] Measuring the gravitational force on sub-meV antiprotons has also been proposed.[3] It may even become possible to produce and study cold antihydrogen,[4] perhaps allowing a measurement of the gravitational force without the severe competition of electrical forces.[5] Although initial slowing and cooling from the GeV energies at which antiprotons are produced and collected is now routinely done in a series of storage rings at CERN, the lowest-energy antiprotons generally available for experiments still have a kinetic energy of 5.9 MeV. These antiprotons are stochastically cooled, stored, and then ejected from the Low Energy Antiproton Ring (LEAR) which was built for this purpose. Lower storage energies (< 3 keV) have been achieved in only one experiment, when several hundred antiprotons were briefly stored in an ion trap.[6] In this Letter, we report the first observation of electron cooling within a particle trap, whereby antiprotons cool via repeated collisions with a buffer gas of cold-trapped electrons.[7] (A neutral buffer gas as used for cooling many trapped ions species would cause the antiprotons to annihilate.) As anticipated,[8] electron cooling is extremely effective compared to adiabatic or resistive cooling, even when the cooling rate for the latter is enhanced using electronic feedback techniques.[9,10] The observed cooling is similar in some respects to the cooling of the hotter species in a two-component plasma,[11] to the cooling of energetic particle beams using a collinear electron beam matched in velocity,[12] and to the sympathetic cooling of one ion species by another in an ion trap.[13]

Pulses of 5.9-MeV antiprotons, typically 250 ns in duration and containing up to 3×10^8 antiprotons, leave our LEAR beam line directed upwards through a Ti window. They pass through another Ti window into a completely sealed vacuum enclosure which is cooled to 4.2 K and located in a 6-T magnetic field. The ion trap inside [Fig. 1(a)] consists of an aluminum plate at the bottom, a series of copper cylinders above which can be separately biased to shape the trapping well, and a copper cylinder of smaller diameter at the top. All the elec-

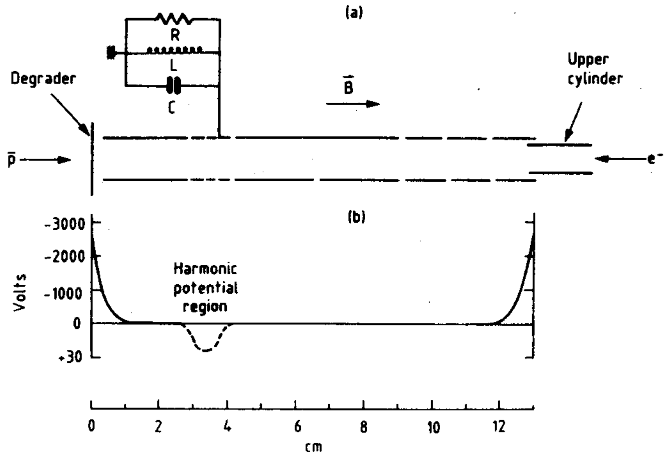

FIG. 1. (a) Trap apparatus and (b) the potential along the axis of the trap.

trodes are gold plated to minimize stray potentials and maximize storage times in the long trap.[14] An earlier version (I) differed by having several electrodes of larger diameter and a flat plate instead of the upper cylinder of smaller diameter. The antiprotons are at approximately 3.7 MeV before they enter the trap by passing through the aluminum plate and their energy is tuned slightly[15] to maximize the number of antiprotons which emerge from this degrader after being slowed below 3 keV. The intense burst of antiprotons also liberates many secondary electrons from the degrader. Many of these are captured in the trap with the antiprotons unless kept from entering the trap by biasing the degrader at +5 V or higher with respect to the first cylinder. In the simplest case [Fig. 1(b)], the cylinders are all grounded except for the upper one which is biased at -3 kV to turn around antiprotons with kinetic energies (along the beam axis) below 3 keV. After the pulse of antiprotons is within the electrodes of the long trap, the potential of the aluminum degrader is quickly switched[16] to -3 kV, completing the ion trap and containing the particles.

After a preset holding time, the potential of the upper plate is ramped through 0 V, a variation of a technique developed for lower energies.[17] For an antiproton of 1 eV or more, the period of the oscillation back and forth along the direction of the magnetic field is very short compared to the 0.1-s ramp, so that antiprotons with energies exceeding the ramp voltage simply leak out of the trap. They annihilate upon striking the vacuum enclosure above (or the plate electrode in trap I), producing on average 3.5 charged pions which are detected in six plastic scintillators which surround the Dewar of the superconducting magnet. Annihilations are detected with an efficiency estimated to exceed 90% (with coincidence signals from two or more scintillators occurring for 36% of the detected annihilations) and are recorded in a multiscaler which starts counting when the voltage ramp starts. The voltage ramp is linear in time. Unless the antiproton energy is exceedingly low, this makes the multiscaler spectrum a direct measure of the energy of motion in the direction of the incident beam and the magnetic field. (Transverse energy stored in the cyclotron motion is not measured directly.) The axial energy spectrum of the antiprotons in the trap before the ramp can differ due to two competing effects. First, lowering the ramp lowers the well depth and hence can adiabatically cool the trapped antiprotons before they escape. However, the cylinders exponentially screen the ramped potential from the interior of the trap so that adiabatic cooling is unimportant for the higher-energy spectrum we display (Fig. 2). Second, the space-charge potential due to electrons and other antiprotons in the trap during the ramp reduces the effective well depth, so that the antiproton distribution before the ramp could actually be slightly lower in energy than measured.

Figure 2 shows an energy spectrum for antiprotons held 100 s in trap I. Approximately 60000 detected annihilations are plotted as a function of the potential of the plate at which the annihilations occurred, with an energy resolution of 6.1 V/channel. A factor of 4 to 5 less trapped antiprotons is more typical, depending on the number of antiprotons in the pulse from LEAR and on

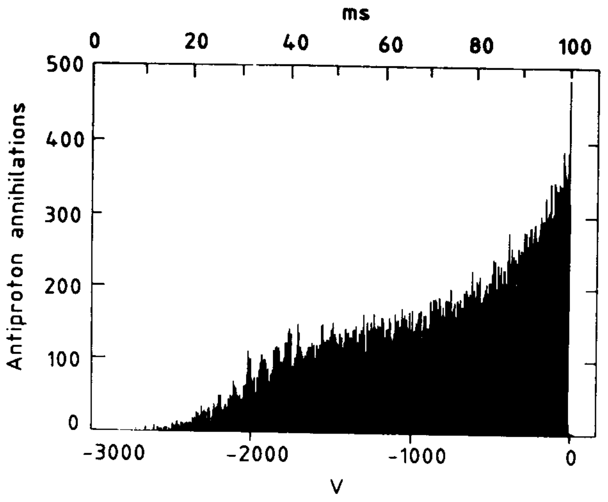

FIG. 2. Spectrum for antiprotons held 100 s.

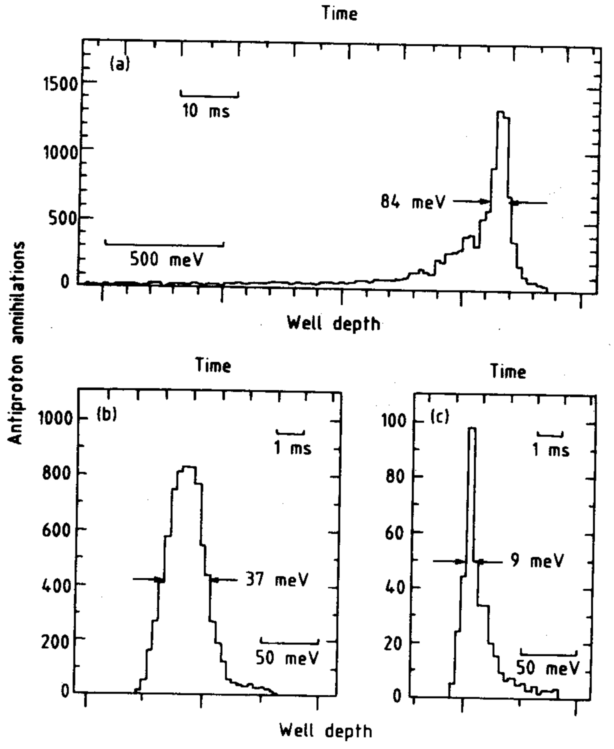

FIG. 3. Three examples of the number of antiprotons detected escaping the harmonic well as a function of the well depth. The well depth is reduced linearly in time at the rates indicated in the insets. Electrons used for cooling are still in the trap in example (a) and most have been removed for (b). In (c), the number of antiprotons has been reduced as well.

how well the beam is focused and steered (at best to a FWHM diameter of 3 mm before entering the vacuum chamber). The spectrum cuts off at 0 V and falls off at higher kinetic energies as the antiproton energy approaches the 3-keV well depth. The pronounced peak at low energies occurs only for the most intense pulses of antiprotons from LEAR. It seems to be due to electron cooling by secondary electrons freed from the degrader and can be eliminated by biasing the degrader as mentioned. Using the number of antiprotons measured to leave LEAR, we capture antiprotons from LEAR with an efficiency of 2×10^{-4}. The real efficiency is certainly higher (since all of the antiprotons leaving LEAR do not arrive at our experiment) and could be increased by applying a larger trapping potential to a longer trap. Antiprotons were routinely held for an hour with no noticeable loss of particles. In one trial, antiprotons were captured and held for 2.7 days (with little change in their 0-3-keV energy spectrum) establishing that the storage lifetime in the long trap was greater than 50 h.

Electron cooling of antiprotons below 1 eV can be observed in the long trap, but is complicated by observed instabilities for low-energy antiprotons and electrons in this kind of trap (cf. Ref. 14). The electron cooling is more controllable when electrons are loaded and monitored (before the antiprotons arrive) in a small region of the long trap. Five of the electrodes, with carefully chosen lengths, are biased to produce a high-quality electric quadrupole potential in the center of this region,[18] as indicated by the dashed line in Fig. 1(b). The shape of the frequency spectrum of the potential developed across a tuned *LCR* circuit connected to one of the electrodes producing the harmonic well [Fig. 1(a)] allows us to estimate the number of electrons[19] which we load into it using a field-emission point. In the examples we show, of order 10^7 electrons were loaded in a harmonic well which is 23 V deep (the well depth is 77.5% of the applied 30-V potential for this electrode geometry[18]) giving an electron density of order $10^8/\mathrm{cm}^3$. The electron number is estimated to be within a factor of 10 of the maximum number of electrons which the Coulomb repulsion allows to be stored in the trap, and represents the largest number of electrons which we were able to work with in a reasonably stable way. The spatial distribution is not well monitored or controlled, but is expected to cover an appreciable fraction of the diameter of the trap. The electrons cool via synchrotron radiation to 4.2 K (with 0.1-s time constant) and also cool via the coupling to the *LCR* which is kept near 4.2 K. The degrader is biased to prevent secondary electrons from entering the trap when the antiprotons arrive.

With electrons waiting in the harmonic well, antiprotons are loaded into the long trap as described earlier. The antiprotons enter and oscillate the length of the long well, cooling via collisions with the cold electrons in the harmonic well. The potential across the *LCR* increases markedly during this preset cooling time. The number of hot antiprotons N_h remaining in the long trap, and their energies, are measured by letting the antiprotons escape and annihilate, exactly as described earlier. A cooled electron spectrum is again observed with the *LCR*. (More antiprotons can be loaded into the long trap at this point, cooled by the same electrons, and stacked in the harmonic well.) The number of cooled antiprotons N_c which now reside with the electrons in the harmonic well is measured by slowly decreasing the depth of the harmonic well, from 23 eV to below 0 eV. Figure 3(a) is an example wherein nearly 14000 antiprotons are released from the harmonic well, annihilate, and are detected in the scintillators. The total number of uncooled and cooled antiprotons, N_h+N_c, is proportional to the number of antiprotons incident from LEAR and independent of the cooling time, indicating that few antiprotons are lost in the cooling process. However, the fraction cooled, $N_c/(N_h+N_c)$, increases with cooling time from 0% to saturation above 90%. The cooled fraction decreases when less electrons are used for cooling and generally varies by approximately 10% from trial to trial, with occasional fluctuations which are larger. The time constant for cooling with the numbers of electrons mentioned is approximately 10 s. This is consistent with the calculated cooling rates[8] for this electron density, but a more quantitative comparison is difficult because the calculation does not include the effect of the strong magnetic field and because of uncertainties about the spatial distribution of the large electron cloud.

The first example [Fig. 3(a)] shows the antiproton spectrum just after electron cooling. The depth of the harmonic well is decreased from 23 eV to below 0 eV at a rate of 23.5 meV/ms, with each channel 1 ms. The well depth presumably decreases through zero at or slightly to the right of the peak. However, this zero crossing is hard to locate precisely since stray potentials within the electrodes are expected to shift the well depth by as much as 100 meV. This means that we cannot prove that the energy of the antiprotons is lower than 100 meV, even though the spread in the antiproton energies is clearly observed to be much less in the three examples shown. The observed half-width in Fig. 3(a) is 84 meV, already 2×10^4 times reduced from the initial width of the trapped antiprotons. The actual spread in the kinetic energies of the particles in the trap may be much lower, with the observed width being a measure of the space-charge potential of the cold electrons and antiprotons in the trap. Consistent with this interpretation, the observed width is reduced to 37 meV in the second example [Fig. 3(b), with 4.7 meV/channel] after most of the electrons are resonantly ejected from the trap (with negligible loss of antiprotons). If in addition we reduce the number of antiprotons in the trap to approximately 400, the observed width decreases to only 9 meV [Fig. 3(c), with 4.7 meV/channel]. This is only 30 times wider than would be expected for thermal equilibrium at 4.2 K and the width may still reflect the space charge rather than the spread in kinetic energies of the trapped antiprotons. At these low energies when the well depth is decreased, other mechanisms may be assisting the electron cooling. The particle distribution will expand and cool as the harmonic well is adiabatically reduced. Also, the hotter trapped particles may be able to evaporate out of the shallow well, leaving a cooler distribution behind. The measured energy distributions are so cold that it should certainly be possible to extract the antiprotons from the harmonic well (as has been done with ions[20]) and accelerate them as desired to produce a (weak) antiproton source with a very narrow energy dispersion.

An electric quadrupole and a magnetic field are suited for long-term storage of charged particles, as illustrated by a single electron so confined more than 10 months.[21] In the longest opportunity to hold cold antiprotons in the harmonic trap of Fig. 1(a), over 8000 antiprotons were held for more than 2 days without detectable particle loss. At the outset, most of the electrons were resonantly ejected, as was done for the antiprotons observed in Fig. 3(b), and the energy spectrum observed after 2 days is very similar to that shown in Fig. 3(b) except for a slightly larger width of 47 meV. When the uncertainty in the initial number of antiprotons is taken into account, we can set a conservative limit that the lifetime for the cold antiprotons in the harmonic trap exceeds 4 days. Comparable lifetimes have been achieved in storage rings, but only with antiprotons of many MeV and higher. At lower energies, cross sections for collisions with background gas atoms are much larger, so lifetimes tend to be much shorter. For example, LEAR stores 5.9-MeV antiprotons with a storage lifetime less than 3 h.[22] The longer lifetime in the trap, despite much lower energies, is possible because an extremely good vacuum can be obtained in a small sealed enclosure at 4.2 K.[23] In an environment suited for precision experiments, it is therefore now possible to experiment for days with extremely cold antiprotons stored more than 6×10^7 times lower in energy than those stored in the lowest-energy antiproton storage ring.

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