Available online at www.sciencedirect.com
SCIENCE DIRECT®

PHYSICS LETTERS B

Physics Letters B 548 (2002) 140–145

www.elsevier.com/locate/npe

Stacking of cold antiprotons

ATRAP Collaboration

G. Gabrielse [a,*], N.S. Bowden [a], P. Oxley [a], A. Speck [a], C.H. Storry [a], J.N. Tan [a], M. Wessels [a], D. Grzonka [b], W. Oelert [b], G. Schepers [b], T. Sefzick [b], J. Walz [c], H. Pittner [d], T.W. Hänsch [d], E.A. Hessels [e]

[a] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[b] *IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[c] *CERN, 1211 Geneva 23, Switzerland*
[d] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[e] *York University, Department of Physics and Astronomy, Toronto, ON M3J 1P3, Canada*

Received 19 September 2002; received in revised form 14 October 2002; accepted 14 October 2002

Editor: L. Montanet

Abstract

The stacking of cold antiprotons is currently the only way to accumulate the large numbers of the cold antiprotons that are needed for low energy experiments. Both the largest possible number and the lowest possible temperature are desired, especially for the production and study of cold antihydrogen. The antiprotons accumulated in our particle trap have an energy 10^{10} times lower than the energy of those delivered by CERN's Antiprotons Decelerator (AD). The number accumulated (more than 0.4 million in this demonstration) is linear in the number of accepted high energy antiproton pulses (32 in this demonstration). Accumulation efficiencies and losses are measured and discussed.

1. Introduction

The existence of antihydrogen atoms was confirmed by the observation of high speed atoms formed in a storage ring, first at CERN [1] and then at Fermilab [2]. Cold antiprotons and positrons enabled us to observe positron-cooling of antiprotons [3], an important step towards the long term goal to produce antihydrogen that is cold enough to confine in a neutral particle trap for precise spectroscopic comparisons with hydrogen [4]. Such a comparison has the potential to substantially improve the accuracy of CPT tests with baryons and leptons [5] and to test for possible extensions to the standard model [6], owing to the high precision attainable with laser spectroscopy [7].

Only if substantial numbers of cold antiprotons are available does it become possible to produce cold antihydrogen that can be trapped for spectroscopy. Collisions with cold matter walls, of course, will cause annihilation before cooling, so the technique used to cool hydrogen for trapping and spectroscopy [8] is not

* Corresponding author.
E-mail address: gabrielse@physics.harvard.edu (G. Gabrielse).

PII: S0370-2693(02)02850-2

an option. “Cold” here refers to cryogenic temperatures, near 4 K or below, since antihydrogen hotter than this is not so useful for particle trapping. Only approximately a percent of antihydrogen atoms from a 4 K thermal distribution can be held in a state-of-the-art superconducting neutral particle trap, about 0.5 K deep for the magnetic moment of ground state antihydrogen atoms. This percentage drops very rapidly with increasing temperature, so hotter antihydrogen atoms will be difficult to capture.

This Letter reports the substantial accumulation of cold antiprotons in an ion trap—up to 0.4 million antiprotons from a sequence of 32 pulses of high energy antiprotons sent to our apparatus. The stacking of cold antiprotons is linear in the number of injection pulses, suggesting that as many antiprotons can be accumulated as time permits. Although some of us demonstrated the basic principles more than a decade ago [5, 9], there was little need for more cold antiprotons at the time. The observed stacking was thus only described briefly, but never investigated extensively nor discussed in the detail that its current importance warrants. All of the current experiments with low energy antiprotons have adopted this technique, to accumulate antiprotons from the CERN Antiproton Decelerator, the only source of antiprotons that can be so cooled and stored. In the future, a radiofrequency quadrupole (RFQ) decelerator together with stacking may allow the accumulation of larger numbers of cold antiprotons [10].

2. Capture of keV antiprotons

Low energy antiproton studies are currently done only at the Antiproton Decelerator (AD), a storage ring built at CERN primarily to make antiprotons available for antihydrogen studies. It delivers 5.3 MeV antiprotons—an energy that is more than 10^{10} times higher than $kT = 0.3$ meV for our 4 K trap. Every 108 seconds a pulse of up to 3×10^7 antiprotons is sent from the AD to an attached experiment. By slowing these in matter [11], trapping them [12], and electron-cooling them in the trap [9], of order 20 000 cold antiprotons are stored from one injection. More cold antiprotons are currently available only if antiprotons are stacked from successive pulses of AD antiprotons, using the technique demonstrated and discussed here.

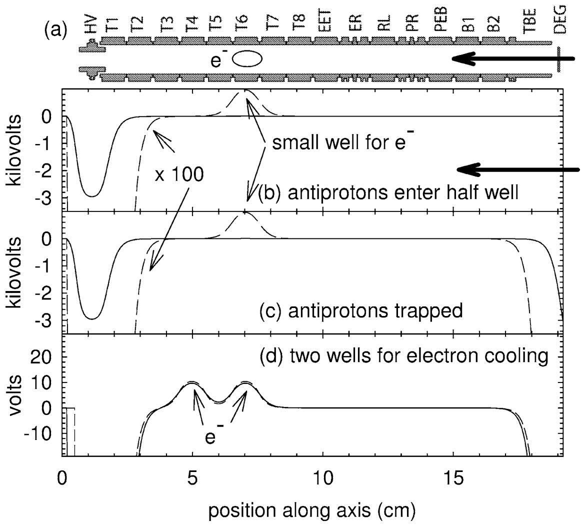

Fig. 1. (a) Cross section of the electrodes used to accumulate cold antiprotons. Voltage applied to the electrodes form different potential well on axis when we await antiprotons (b) and capture and electron-cool antiprotons in one (c) or two (d) electron wells.

Antiprotons are captured and cooled within a Penning trap. A 5.4 Tesla magnetic field from a superconducting solenoid is directed along the vertical axis of a stack of copper ring electrodes (Fig. 1(a)) with a 1.2 cm inner diameter. The electrodes and surrounding vacuum enclosure are cooled to 4.2 K via a thermal contact to liquid helium. Cryopumping reduces the pressure within the trap to less than 5×10^{-17} Torr (7×10^{-15} Pa and 7×10^{-17} mbar), as measured in a similar apparatus [9] using the lifetime of trapped antiprotons as the vacuum gauge.

With the trap biased to form half a potential well (Fig. 1(b)), a pulse of antiprotons from the AD enters from the bottom (arrow from right in the figure), some of them slowing below 3 keV as they pass through the thin beryllium window (labelled as degrader DEG). These slower antiprotons, guided by the 5.4 Tesla magnetic field directed along the axis of the trap, reflect from the potential barrier at the top of the trap. Before they can return to the entrance of the trap and escape, the potential on the thin window degrader is made suddenly negative (Fig. 1(c)) to capture the antiprotons. We refer to this potential well that extends the whole length of the trap as the “long well”. We do so to distinguish it from the “short well” just visible in the expanded view of the potentials (electrode T6

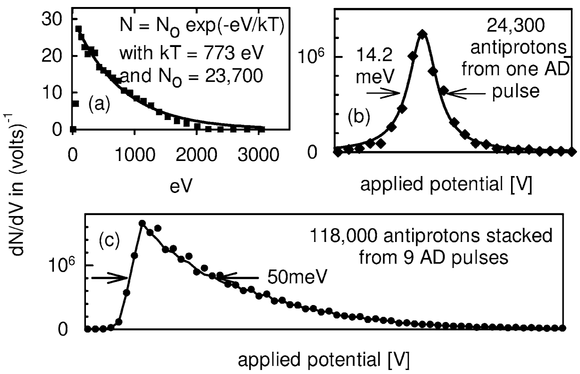

Fig. 2. Energy spectra for antiprotons trapped from a single pulse from the AD without (a) and with (b) electron cooling. Stacking (c) yields a much larger number of cold antiprotons. The insets to (b) and (c) indicate the linear voltage scale; no absolute voltages are given since tiny offset voltages are not calibrated.

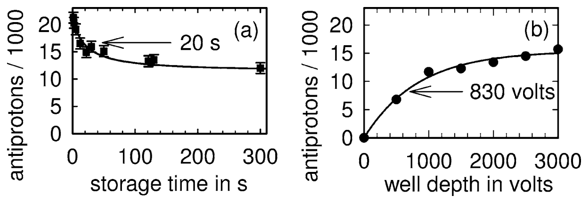

Fig. 3. Number of antiprotons captured from an AD pulse has approximately an exponential dependence upon storage time (a) and well depth (b) with the $1/e$ values indicated.

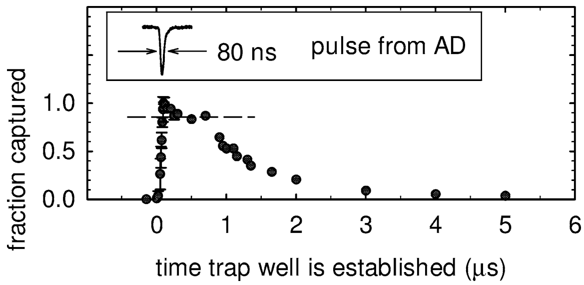

Fig. 4. Number of trapped antiprotons depends upon when the trapping potential is applied.

in Fig. 1(b) and (c)) that will be central in the coming discussion of electron-cooling and stacking.

The number and energy distributions of the hot antiprotons captured is measured by slowly ramping the potential of the degrader window back through zero. The highest energy antiprotons escape first and the charged pions from their annihilation are detected with essentially unit efficiency in scintillators that surround the trap apparatus [3]. Antiprotons held for tens of seconds or more show a characteristic energy spectrum that is nearly exponential (Fig. 2(a)). Almost 25 000 antiprotons have been captured in the long well from the most intense AD pulses, but 13 000–16 000 is more typical. Typically 7×10^{-4} of the antiprotons ejected from the AD are in our long well after 30 seconds, slightly higher than reported for a similar trap at LEAR [5].

These numbers refer to antiprotons remaining after losses we observed during the first seconds of antiproton capture (Fig. 3(a)) as captured antiprotons collide and some leave the trap. The number of captured antiprotons increases as the depth of the long potential well is increased (Fig. 3(b)). One might expect this increase to be linear insofar as the energy distribution of antiprotons slowed in the degrader window is expected to be hundreds of keV—much wider than the energy of antiprotons we can capture. However, we observe that the number captured saturates, presumably because particles with more energy along the trap axis also typically have more radial energy and this can cause them to hit the trap electrodes. It may be that a trap with a larger radius may restore a linear increase in trapped particles with well depth.

The 80 ns duration of the entering pulse of antiprotons (inset to Fig. 4) is narrow compared to the typical round trip time for captured antiprotons. Antiprotons with the average energy of 773 eV in Fig. 2(a), for example, have a round trip time of 900 ns. Fig. 4 shows how the maximum number of antiprotons are captured in the long well by making the sudden potential change just after the pulse of antiprotons enters the trap. Delaying this potential change decreases the number of captured antiprotons since the faster ones return to hit the degrader window before capture. The number of captured antiprotons stays rather flat (dashed line segment in the figure) during the round trip time it takes for the faster antiprotons to return to the trap entrance.

3. Electron cooling and stacking

Electrons for electron cooling are loaded for these studies using a positron beam sent through the trap. It creates secondary electrons when it strikes the degrader (DEG). We capture these electrons and transfer them to electrode T6 before accepting antiprotons into the trap. The details of the electron loading are not so important for our purposes here since we often instead load electrons using a field emission point as has been described before [9]. For these studies, about 4 million electrons are used. Their cyclotron motion cools via the spontaneous emission of synchrotron radiation with a 0.1 second time constant, and their oscillatory axial motion along the magnetic field direction cools via collisional coupling to the cyclotron motion. Magnetron motion is not cooled for these studies.

With cold electrons ready for electron cooling, antiprotons are captured into the long well as described above. Fig. 5 shows the shifting energy spectrum of antiprotons remaining in the long well for increasing electron cooling times. Cooled antiprotons join the electrons in the small well and hence do not show up in these spectra. Antiprotons away from the center of the trap, outside the 4 mm radius of the electron cloud, are not electron-cooled even after a long time in the trap. Fig. 6 shows how many antiprotons are captured in the long well, not cooled by the electrons, cooled into the small well, and spilled from the long well from a single pulse of antiprotons from the AD. The number of annihilations of antiprotons that spill from the trap is plotted as a function of time in Fig. 7(a). Presumably these antiprotons are barely bound in the trap and are nudged out by collisions with other antiprotons. Two AD injection cycles are shown in this figure. The narrow peaks occur when antiprotons are released from the long well to analyze their energies, and to prepare for the next AD pulse.

We eject the electrons in the small well with the cooled antiprotons by repeatedly opening the small potential well for 100 ns. The less massive electrons escape leaving the heavier antiprotons behind to be recaptured when the well is restored. Fig. 2(b) and (c) shows spectra of antiprotons released as the depth of the small well is slowly reduced and the number of antiproton annihilations is measured as a function of the well depth. The widths of the observed low energy distributions (Fig. 2(b) and (c)) are difficult to interpret. The electrons are in thermal equilibrium with their 4 K environment, and the antiprotons in turn come to thermal equilibrium with the electrons. A 4 K energy width is only 0.3 meV. This is much smaller than the observed widths, which depend upon space charge [9] (about 10 mV is estimated for

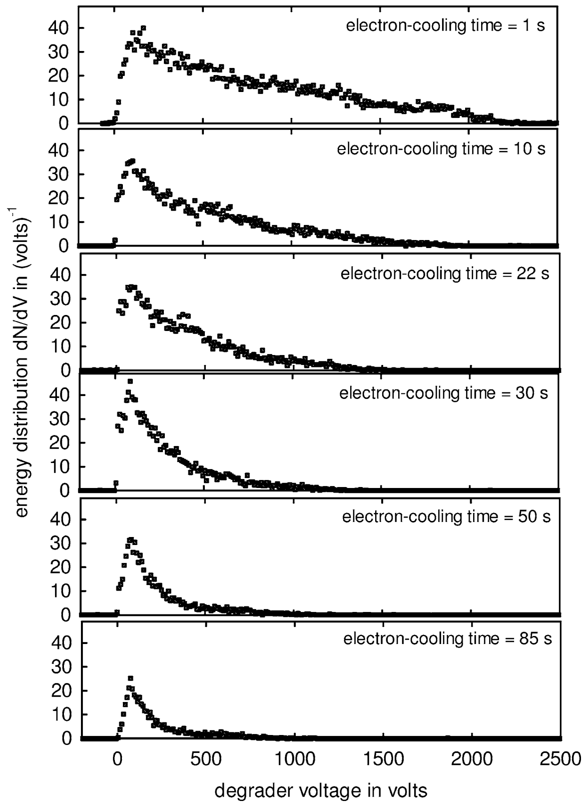

Fig. 5. The energy of the antiprotons in the long well decreases as a function of electron cooling time. The number also decreases insofar as some antiprotons are cooled into the small well and others are lost from the trap.

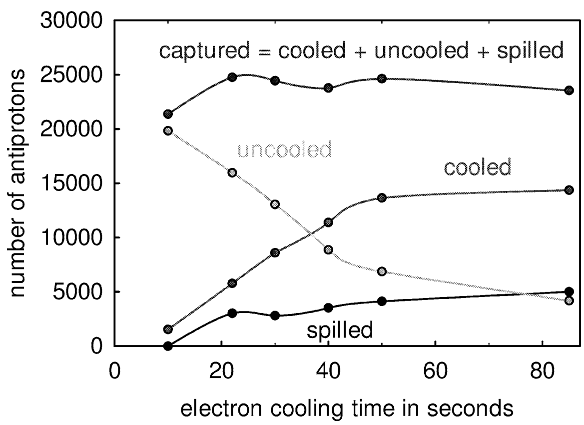

Fig. 6. Number of antiprotons captured, uncooled, spilled and cooled from a single pulse of AD antiprotons.

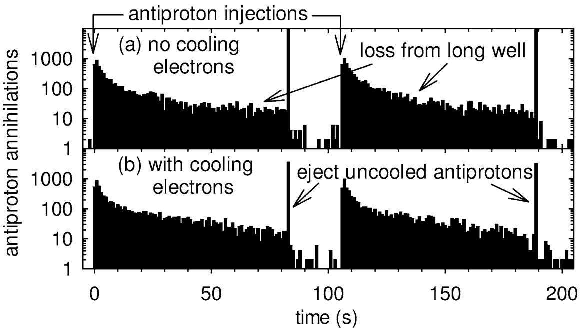

Fig. 7. AD antiprotons are injected into the long trap every 108 s. For the subsequent 85 s, with or without cooling electrons, the number lost is approximately the same, but electrons cool some into the small well (or wells). Uncooled antiprotons remaining in the long well are then ejected.

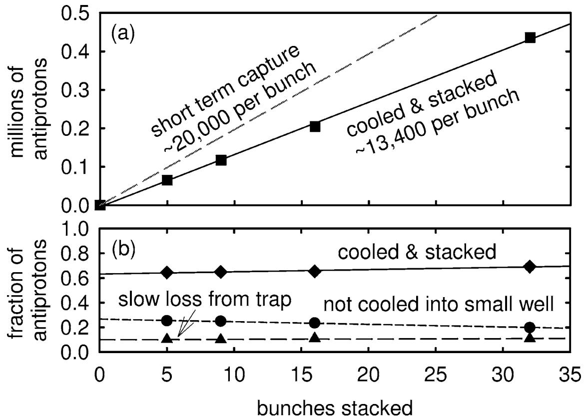

Fig. 8. Stacking successive pulses of antiprotons.

25 000 antiprotons) and upon radial dependences of the trapping field (typically 20% variations for a 6 mm radius, or about 10 mV). There is also adiabatic cooling as the well depth is reduced.

If more than 20 000 cold antiprotons are desired then it is necessary to accumulate antiprotons from more than one pulse of antiprotons from the AD. After cooling antiprotons from one AD pulse for 85 seconds, as described above, the cooled antiprotons reside with the electrons in the small well. We then remove the high voltage potential on the degrader window, and count the uncooled antiprotons thereby released from the long well. The long trap is now ready to capture and cool a second pulse of antiprotons from the AD. Fig. 7 shows a time record of antiproton annihilations detected as antiprotons are injected into the trap, held with and without electron-cooling, and then released.

The basic idea of antiproton stacking in a trap is to accumulate cold antiprotons from as many pulses from the AD as we like. Some of us demonstrated such stacking long ago, but only for a few pulses of antiprotons [9]. The applications at the time did not require many antiprotons, and LEAR pulses delivered about 100 times more antiprotons than the AD delivers. The crucial demonstration in this report is the linear accumulation of cold antiprotons as a function of the number of AD antiproton pulses injected into the trap in Fig. 8(a). We have accumulated up 18 000 antiprotons per AD pulse when the AD was operating at its best (16 000 is more typical) but for these systematic studies the accumulation rate was lower. The dashed line above in this figure includes antiprotons that are initially captured in the trap, but then spilled quickly as discussed. We continuously monitor all antiproton annihilations during the whole process, except for 2 to 10 seconds following an AD pulse during which our detectors are turned off to protect them from the large injection signal.

The near unit detection efficiency allows us to identify antiproton losses at nearly any time during the cycle. Fig. 8(b) gives more details. About 20% of the initially captured antiprotons are not cooled by the electrons and are lost when the long well is opened to prepare for accepting the next pulse. About 10% of the initially captured antiprotons are lost from the traps during the electron cooling process. A little more than 60% of the initially captured antiprotons are cooled into the small well and are available for as long as desired for experiments.

Since the antiprotons that spill from the trap during the cooling time, whether or not cooling takes place, are not really trapped for any significant time, a convenient way to normalize is to compare the number of antiprotons accumulated in the small well per antiproton pulse to the number of antiprotons captured in the long well when no cooling electrons are in the small well [9]. This ratio is typically 1.0 for the 85 second electron cooling time we generally use. This efficiency depends upon the details of the number and spatial distribution of the cooling electrons, the number of wells these are contained in, etc.

The antiproton stacking study in Fig. 8 was carried out with electrons in only the T6 potential well

(Fig. 1(a)). We have observed that if we stack more than the 30 bunches shown, the "slow" loss from the long well between injections (Fig. 7) increases sharply, keeping us from accumulating more cold antiprotons. We then must use multiple wells for electron-cooling to accumulate more antiprotons. Fig. 1(d) shows a two well structure we have used, and we have used more wells.

We have loaded more cooling electrons using a field emission point near the center axis of the trap. This is much faster with the result that we typically loaded 8 million electrons for electron cooling. This larger number of electrons occupied a volume that extended to larger radii (about 5 mm), away from the trap axis. As might be expected, fewer antiprotons were left uncooled by the cooling electrons in this case, about 5%. However, the "slow" loss increases to 35% to just compensate.

4. Conclusions

In conclusion, cold antiprotons with temperatures near to 4 K can be accumulated from a sequence of pulses of high energy antiprotons. The crucial result is that cold antiprotons accumulate in proportion to the number of high energy antiproton pulses sent to the trap. Electron-cooling is key to this stacking technique. A careful measurement of antiproton losses during the accumulation process indicates where further optimization can be sought. Meanwhile, antiprotons can be accumulated linearly in time for low energy experiments where larger numbers of cold antiprotons are needed than can be obtained from single pulses of high energy antiprotons. Experiments to produce cold antihydrogen, for example, will rely on this antiproton stacking techniques.

Acknowledgements

We are grateful to the CERN, its PS Division and the AD team for delivering the high energy antiprotons. This work was supported by the NSF, AFOSR, the ONR of the US, the BMBF and MPG of Germany, and the NSERC, CRC and PREA of Canada.

References

[1] G. Baur, G. Boero, S. Brauksiepe, A. Buzzo, W. Eyrich, R. Geyer, D. Grzonka, J. Hauffe, K. Kilian, M.L. Vetere, M. Macri, M. Moosburger, R. Nellen, W. Oelert, S. Passagio, A. Pozzo, K. Rohrich, K. Sachs, G. Scheppers, T. Sefsick, R.S. Simon, R. Stratmann, F. Stinzing, M. Wolke, Phys. Lett. B 368 (1996) 251.
[2] G. Blanford, et al., Phys. Rev. Lett. 80 (1998) 3037.
[3] G. Gabrielse, J. Estrada, J.N. Tan, P. Yesley, N.S. Bowden, P. Oxley, T. Roach, C.H. Storry, M. Wessels, J. Tan, D. Grzonka, W. Oelert, G. Scheppers, T. Sefsick, W. Breunlich, M. Carngelli, H. Fuhrmann, R. King, R. Ursin, H. Zmeskal, H. Kalinowsky, C. Wesdorp, J. Walz, K.S.E. Eikema, T.W. Hänsch, Phys. Lett. B 507 (2001) 1.
[4] G. Gabrielse, in: P. Bloch, P. Paulopoulos, R. Klapisch (Eds.), Fundamental Symmetries, Plenum, New York, 1987, p. 59.
[5] G. Gabrielse, Adv. At. Mol. Opt. Phys. 45 (2000) 1.
[6] R. Bluhm, V.A. Kostelecký, N. Russell, Phys. Rev. D 57 (1998) 3932.
[7] C. Zimmerman, T. Hänsch, Hyper. Int. 76 (1993) 47.
[8] H.F. Hess, G.P. Kochanski, J.M. Doyle, N. Masuhara, D. Kleppner, T.J. Greytak, Phys. Rev. Lett. 59 (1987) 672.
[9] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells, Phys. Rev. Lett. 63 (1989) 1360.
[10] M. Hori, et al., Nucl. Phys. A 692 (2001) 119.
[11] G. Gabrielse, X. Fei, L.A. Orozco, S.L. Rolston, R.L. Tjoelker, T.A. Trainor, J. Haas, H. Kalinowsky, W. Kells, Phys. Rev. A 40 (1989) 481.
[12] G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R.L. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, W. Kells, Phys. Rev. Lett. 57 (1986) 2504.