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The ingredients of cold antihydrogen: Simultaneous confinement of antiprotons and positrons at 4 K

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Abstract

Low energy antiprotons and cold positrons are stored together and observed to interact for the first time. The particles and the nested Penning trap that confines them are cooled to 4.2 K, within a vacuum better than 5×10^{-17} Torr. The simultaneous confinement clearly demonstrates the potential of a nested Penning trap for the production of cold antihydrogen. Contaminant ions play a deleterious role, and we observe a surprising coupling between the positron and antiproton accumulation mechanisms. © 1999 Published by Elsevier Science B.V. All rights reserved.

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Observations of antihydrogen at CERN [1] and Fermilab [2] generated widespread interest in the study of this simplest antimatter atom. A few observed detector events were attributed to the annihilation of antihydrogen constituents as these struck the detectors while traveling at nearly the speed of light. Cold antihydrogen, at energies low enough to be trapped for precise spectroscopy, has clear advantages for an accurate comparison of antihydrogen ($\overline{\mathrm{H}}$) and hydrogen (H). The most important of these is a much longer time for precision measurement of the properties of ($\overline{\mathrm{H}}$) and H. The pursuit of cold antihydrogen [3] began some time ago, just after antiprotons were first slowed and trapped [4]. Subsequently, the accumulation of both cold antiprotons [5] and cold positrons [6] in extremely high vacuum has become common, as has the trapping of atoms [7] including hydrogen [8]. A substantial ''Antiproton Decelerator'' (AD) facility is now under construction at CERN to carry forward experiments with low energy antiprotons, and two large collaborations (ATRAP [9] and ATHENA [10]) have formed to produce and study cold antihydrogen.

In this Letter we report the first simultaneous confinement and interaction of 4 K antiprotons and positrons, at a background pressure shown to be better than 5×10^{-17} Torr in a similar apparatus [5]. This demonstration with the ingredients of cold anti-

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hydrogen shows it is feasible to overcome the special challenges posed by two species of antimatter particles. Unlike their matter counterparts, both antimatter species readily annihilate upon any contact with matter containers and background gas. Also, their sources (an accelerator ring for $\bar{p}$ and a radioactive source for e^+) offer challenges not posed by sources of protons and electrons. The e^+ and $\bar{p}$ eventually reside in a nested Penning trap virtually identical to that used previously to cool electrons and protons to the low relative velocity [11] needed to efficiently form cold hydrogen or antihydrogen. The demonstration with e^+ and $\bar{p}$ took place during the last nine days of operation of the Low Energy Antiproton Ring (LEAR) at CERN.

The Penning trap structure used to capture and confine $\bar{p}$ and e^+ (Fig. 1a) consists of a 6 Tesla magnetic field directed along the symmetry axis of a stack of coaxial, gold-plated copper ring electrodes. Each of these electrodes is biased independently as needed to trap particles (*e.g.* Fig. 1b) and to move them adiabatically from one location to another. Positrons and antiprotons are trapped and counted

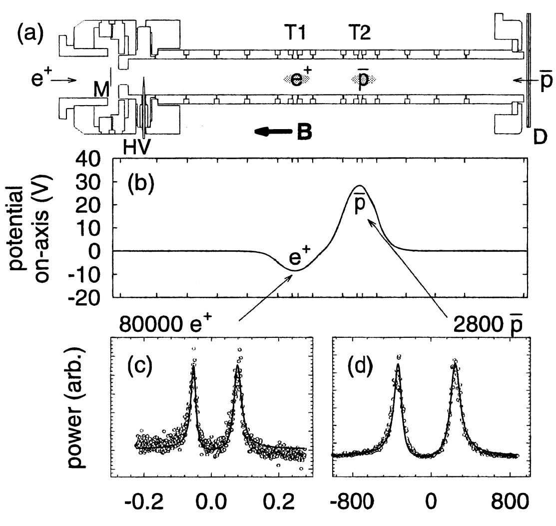

Fig. 1. (a) Electrode cross sections and the initial position of the simultaneously trapped $\bar{p}$ and e^+. (b) Trap potential on the symmetry axis. Fits (solid curves) to the electrical signals from simultaneously trapped e^+ (c) and $\bar{p}$ (d) establish the number of trapped particles.

nondestructively in two highly harmonic regions of the trap [12] (T1 and T2 in Fig. 1a).

For an empty trap, the measured Johnson noise across an RLC circuit attached to electrodes in each region is a Lorentzian centered at the circuit's resonant frequency. The harmonic oscillation of trapped particles along the magnetic field direction shorts the Johnson noise at the resonant frequency of the particles. The resulting notches in the observed spectra (*e.g.* Fig. 1c-d, Fig. 3b and Fig. 4a) grow with the number of trapped particles [13] and allow nondestructive measurements of the number of trapped e^+ and $\bar{p}$. The trap electrodes are within a completely enclosed vacuum vessel which is cooled to 4 K by thermal contact to liquid helium, thereby achieving the extremely good vacuum mentioned.

We reduce the energy of antiprotons from LEAR by more than 10 orders of magnitude using techniques developed by our TRAP collaboration [4,14,5] for improved comparisons of the charge-to-mass ratios of the antiproton and proton [15]. A 250 ns pulse of up to 3×10^8 antiprotons at 5.9 MeV leaves our LEAR beamline directed along the axis of the trap. The $\bar{p}$ pass through 10 μm Ti windows to enter the sealed vacuum enclosure that contains the Penning trap. The $\bar{p}$ energy is tuned slightly, by sending them through an adjustable gas mixture [16], to optimize the number of antiprotons that slow in the degrader electrode (D in Fig. 1a) and emerge with energies below 3 keV. These $\bar{p}$ reflect from the -3 kV potential applied to the uppermost electrode (HV in Fig. 1a) and are trapped when the degrader potential is switched suddenly [17] to -3 kV.

Of order 10^7 electrons are preloaded in one of the harmonic regions before the $\bar{p}$ arrive, and these cool via synchrotron radiation to the 4.2 K temperature of their surroundings. Trapped $\bar{p}$ then cool via collisions with the cold trapped electrons [14]. As many $\bar{p}$ as will fit, limited by space charge, end up in the small harmonic well with the cooling electrons. The rest are cooled but remain in the long well between the degrader and the uppermost electrode. Their energy is analyzed by reducing the potential at one end of the long well while external scintillators detect pions from antiprotons that escape the trap and annihilate upon striking the trap electrodes or vacuum enclosure. Fig. 2a shows the energy distribution of 0.2 million $\bar{p}$ as they are released from the

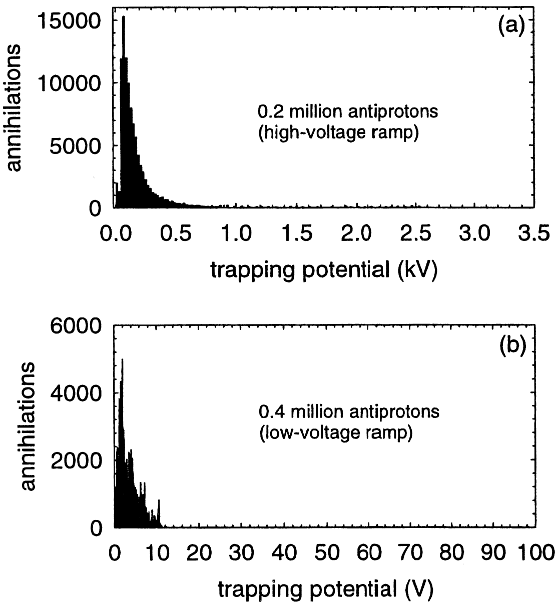

Fig. 2. Approximately 0.6 million $\bar{p}$ are captured from a 250 ns pulse of antiprotons from LEAR. Two thirds were cooled sufficiently to fit into the central harmonic well with the electrons (b), while the rest remained in the long well (a).

long well. Similarly decreasing the trapping potential for the small well (Fig. 2b) releases an additional 0.4 million cold $\bar{p}$, for a total of 0.6 million trapped $\bar{p}$ from a single intense LEAR pulse. We can typically capture 5×10^{-4} of the $\bar{p}$ pulsed out of LEAR.

A simple and efficient new technique is used to accumulate positrons directly into the extremely high vacuum of a cryogenic apparatus at 4 K. The unusual mechanism for this e^+ accumulation, believed to be the ionization of slow positronium atoms initially formed in very high Rydberg states, will be the subject of a separate publication as soon as experimental tests are completed. Here we simply describe the experimental configuration [19]. Positrons emerge from a ^{22}Na source with energies up to 0.5 MeV. They pass through the 100 face of a 2 μm tungsten crystal (M in Fig. 1a), picking up electrons as they leave. The electric fields in the trapping volume ionize the Rydberg positronium leaving positrons trapped in this small region (Fig. 1a).

With only a 5 mCi source, the positron accumulation rate is up to 5×10^4/hr, and more than 10^6 positrons have been accumulated (Fig. 3). (The increase in the number of trapped e^+ is less linear than usual in Fig. 3 because other parts of the apparatus were being installed and tested during this accumulation.) The accumulation technique is also quite robust; over months of loading, and repeated cycling of the apparatus between 300 K and 4 K, the peak loading rate stayed the same. The accumulation rate and the total number of cold positrons accumulated greatly improve upon the two previous accumulations into high vacuum. In the earliest, up to 10^2 e^+ were loaded for a precision measurement [18]. In the other experiment [6], electronic damping of positrons slowed in a tungsten crystal yielded up to 3×10^4 e^+ positrons accumulated at a rate of up to 1.2×10^3/hr.

So far we have shown that large numbers of cold antiprotons and cold positrons can be accumulated and stored in the trap of Fig. 1a at different times. We now discuss the simultaneous confinement and interaction of $\bar{p}$ and e^+. Fig. 1c-d shows the electrical signals that demonstrate simultaneous confinement within the same trap structure and vacuum enclosure. The size of the notches in the Johnson noise across the attached LCR circuits indicate that

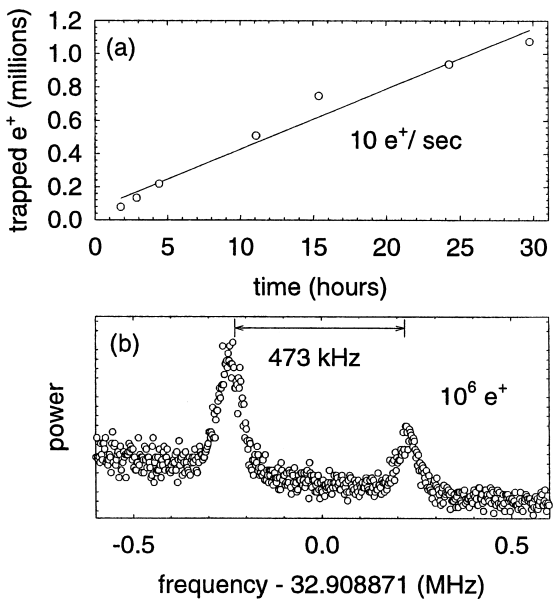

Fig. 3. (a) Accumulation of 1.1 million positrons, proceeding at an average rate of $10\,e^+/s$ despite numerous disturbances for apparatus installation and testing. (b) The electrical signal of the 1.1 million positrons.

8.0×10^4 positrons and 2.8×10^3 antiprotons were confined at the same time. The small number of antiprotons was first captured, cooled by electrons, and the cooling electrons ejected (as described earlier). The positrons were then accumulated over roughly two hours. A second example (Fig. 4) shows the interaction of low energy $\bar{p}$ and cold e^+. The electrical signal from 5.7×10^4 cold positrons (Fig. 4a) shows significant heating (Fig. 4b) when $\bar{p}$, initially trapped with energies up to 3 keV, cool via collisions with them.

Similar numbers of electrons and protons were investigated in preparation for this experiment within a virtually identical set of electrodes, configured as a nested Penning trap [11]. Protons in a potential well were cooled by electrons in a small inverted potential well that was nested within. The cooling self-arrested when the protons and electrons had a very small relative velocity. The protons subsequently maintained an energy well above the lowest energy possible in their potential well.

With $\bar{p}$ and e^+ we observe differences – the $\bar{p}$ continued to cool to the bottom of their potential wells, and fewer than expected remained to be detected. While it would be tempting to attribute the $\bar{p}$ loss to the formation of cold antihydrogen (which would not be trapped by our fields), our experience with protons and electrons leads us to attribute the additional cooling to contaminant electrons loaded into the antiproton wells, and the loss to collisions with contaminant positive ions loaded into the positron well, both contaminants being loaded when antiprotons are injected into the trap. It is now routine to eliminate positive ion contaminants loaded with small numbers of protons using various noise broadened driving forces. In the short duration of this experiment, however, we were not able to generalize these techniques to eliminate the contaminants loaded during intense $\bar{p}$ injections. The contaminant difficulty is especially pronounced when positron cooling is used as a replacement for electron cooling to cool freshly captured keV $\bar{p}$.

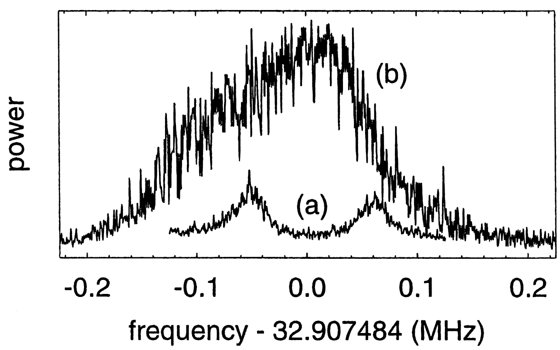

Fig. 4. The signal from cold trapped positrons (below) changes dramatically (above) when heated antiprotons pass through cold positrons in a nested Penning trap, showing the interaction of antiprotons and positrons.

Given that nearly a million $\bar{p}$, and slightly more than a million e^+, were trapped in the trap of Fig. 1a at separate times, we attempted to simultaneously confine large numbers of these particles to make them interact. However, we discovered that repeated $\bar{p}$ injections made the subsequent e^+ loading rate drop to a very low value. Simply warming the trap to room temperature, then cooling it back to 4 K, completely restored the e^+ accumulation rate. Unfortunately, this process took about 24 hours and we only had time to repeat it twice during the nine day run. In our second trial we were very careful to keep trapped $\bar{p}$ from striking and annihilating on the crystal moderator but this did not prevent the diminished e^+ accumulation. We do not yet completely understand the reversible loss of e^+ accumulation. Because merely warming to room temperature restores the accumulation, we presume that it relies upon gas adsorbed on the moderator surface. Intense injections of antiprotons would deplete the layer of adsorbed gas, and warming to room temperature would restore it. Spatially separating the regions in which positrons and antiprotons are initially accumulated should prevent such loss of positron accumulation.

In conclusion, we demonstrate that 4 K antiprotons and 4 K positrons can be accumulated within the same vacuum space, and that low energy $\bar{p}$ and cold e^+ can be made to interact within a nested Penning trap. This bodes well for the large efforts underway to produce and study cold antihydrogen. The mystery of the reversible cessation of e^+ loading when large numbers of $\bar{p}$ are injected, however, remains to be solved. Also, observations that $\bar{p}$ loading introduces positive ion contaminants into previously accumulated positrons (a situation not easy to simulate with matter particles), serve as a warning. Antiproton annihilation when positrons and antiprotons interact may signify the presence of contaminants rather than the formation of cold antihydrogen. Insofar as a variety of solutions are available for both challenges, however, the path to the production and study of cold antihydrogen appears open.

Acknowledgements

We are grateful to the LEAR staff and the CERN management for providing the MeV antiprotons that we used over eleven years to develop the slowing, trapping and cooling techniques that will be used to make cold antihydrogen. It is fitting that the last nine days of LEAR operation were devoted to demonstrating that these techniques could produce the simultaneous confinement of cold antiprotons and positrons, opening the way to a new era of antihydrogen studies at the new Antiproton Decelerator now under construction at CERN. This work was supported by AFOSR, NSF and ONR of the US, and by the BMBF of Germany.

References

[1] G. Baur et al., Phys. Lett. B 368 (1996) 251.
[2] G. Blanford et al., Phys. Rev. Lett. 80 (1998) 3037.
[3] G. Gabrielse, in: P. Bloch, P. Paulopoulos, R. Klapisch (Eds.), Fundamental Symmetries, Plenum, New York, 1987, p. 59.
[4] G. Gabrielse, X. Fei, K. Helmerson, S. Rolston, R. Tjoelker, T. Trainor, H. Kalinowsky, J. Haas, W. Kells, Phys. Rev. Lett. 57 (1986) 2504.
[5] G. Gabrielse, X. Fei, L. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T. Trainor, W. Kells, Phys. Rev. Lett. 65 (1990) 1317.
[6] L. Haarsma, K. Abdullah, G. Gabrielse, Phys. Rev. Lett. 75 (1995) 806.
[7] A.J. Migdall et al., Phys. Rev. Lett. 54 (1985) 2596.
[8] C. Cesar, D. Fried, T. Killian, A. Polcyn, J. Sandberg, I. Yu, T. Greytak, D. Kleppner, J. Doyle, Phys. Rev. Lett. 77 (1996) 255.
[9] ATRAP proposal to the CERN SPSLC, CERN SPSLC/P306, 25 March 1997.
[10] Athena proposal to the CERN SPSLC, CERN SPSLC/P302, 20 October 1996.
[11] D.S. Hall, G. Gabrielse, Phys. Rev. Lett. 77 (1996) 1962.
[12] G. Gabrielse, L. Haarsma, S. Rolston, Intern. J. Mass Spectr. Ion Phys. 88 (1989) 319; 93 (1989) 121.
[13] D. Wineland, H. Dehmelt, J. Appl. Phys. 46 (1975) 919.
[14] G. Gabrielse, X. Fei, L. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T. Trainor, W. Kells, Phys. Rev. Lett. 63 (1989) 1360.
[15] G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky, W. Jhe, submitted to Phys. Rev. Lett.
[16] G. Gabrielse, X. Fei, L. Orozco, S. Rolston, R. Tjoelker, T. Trainor, J. Haas, H. Kalinowsky, W. Kells, Phys. Rev. A 40 (1989) 481.
[17] X. Fei, R. Davisson, G. Gabrielse, Rev. Sci. Instrum. 58 (1987) 2197.
[18] R.S. Van Dyck Jr., P. Schwinberg, H. Dehmelt, Phys. Rev. Lett. 59 (1987) 26.
[19] D.S. Hall, Ph.D. thesis, Harvard University, 1997.