

## Extremely Cold Positrons Accumulated Electronically in Ultrahigh Vacuum

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Many cold positrons in ultrahigh vacuum are required to produce cold antihydrogen, to cool highly stripped ions, and for ultracold plasma studies. Up to  $3.5 \times 10^4$  such positrons have now been accumulated into the ultrahigh vacuum of a 4.2 K Penning trap, at a rate exceeding  $10^3$ /h. Both the accumulation rate (per high energy positron incident at the trap) and the number accumulated are much larger than ever before realized at low temperatures in high vacuum. The cooling of high energy positrons (from  $^{22}\text{Na}$  decay) in a tungsten crystal near the trap, together with purely electronic trapping and damping, is the key to the efficient accumulation and to projected improvements.

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Extremely cold (4.2 K) positrons in the same volume with the  $2 \times 10^5$  antiprotons stored earlier at 4.2 K [1] would produce cold antihydrogen at a high instantaneous rate [2], even in the presence of a strong magnetic field [3]. This cold antihydrogen could be confined and studied in a magnetic gradient trap as is done with hydrogen [4]. Spectroscopic comparison of hydrogen and antihydrogen [5] would test *CPT* invariance even more accurately than a recent  $10^{-9}$  comparison of antiproton and proton charge-to-mass ratios [6], which is currently the most precise test of *CPT* invariance with baryons. Also, a direct measurement of the gravitational force on antimatter might eventually be possible [7]. Cold positron plasmas could also cool highly stripped ions, just as electrons cool hot trapped antiprotons [8], provided the vacuum is sufficient to avoid charge-exchange collisions with residual atoms. An extremely low pressure is also required to avoid annihilations while cold antihydrogen is stored and studied, and during the considerable time which will likely be required to initially produce antihydrogen at a slow rate.

This Letter describes purely electronic positron accumulation in an environment suited for antihydrogen production. Although not measured here, the vacuum in a similar apparatus was demonstrated (with trapped antiprotons) to be less than  $5 \times 10^{-17}$  Torr [1]. This would allow antihydrogen to be stored for months. A crucial feature is that high energy positrons from a radioactive source slow at the trap within a tungsten "moderator" crystal [9]. The greatly compressed, sub-eV energy distribution of the cooled positrons which emerge from the crystal makes it possible to capture electronically a substantial number, with no collisions needed [10]. The result is a positron trapping rate into high vacuum, per high energy positron incident at the trap, that is 20 times higher than previously observed. To date, up to 35 000 positrons are trapped in high vacuum at 4.2 K. This is already enough cold positrons for ion cooling applications. The purely electronic capture mechanism is clearly established [11] and well enough understood to suggest that improved

accumulation rates, along with longer accumulations, will yield the positrons required for cold antihydrogen. A desirable feature of this positron accumulator is that it requires no major facility (e.g., an electron LINAC) which must be relocated at an antiproton or heavy ion facility.

To permit an accurate comparison of the magnetic moment of a single electron and positron [12], a small number of positrons ( $\approx 100$ ) were accumulated earlier into high vacuum in a Penning trap [13,14]. Unfortunately, far too few positrons were trapped for the applications mentioned. The intention was to capture 50 keV positrons directly from a radioactive source, and most of these would not damp electronically because of relativistic frequency shifts [13,14] (out of resonance with a damping circuit). However, the actual loading mechanism for the observed accumulation seems not to be the purely electronic trapping of 50 keV positrons that was proposed [15] and reported. When an error is corrected [16], the calculated accumulation rate turns out to be  $10^3$  times lower than the observed loading rate. This suggests that the actual loading mechanism is not yet understood, and makes it difficult to see how this technique could be scaled up by the large factor needed to produce positrons for antihydrogen and ion cooling. (Alternate explanations are now being explored [17] as a response to this work.) In a different experiment [18], collisions with  $10^{-8}$  Torr (and higher) of a neutral buffer gas yield up to  $10^8$  trapped positrons. The large number is extremely attractive, but the necessarily poor vacuum, short annihilation times, and high positron temperatures make this accumulation method less compatible with the desired applications, as is a less efficient pulsed method [19].

In our apparatus, a 10 mCi  $^{22}\text{Na}$  source of high energy positrons (up to 0.5 MeV) is located 20 cm above the Penning trap and moderator crystal. The separation of source and trap facilitates shielding the intense source. It also enables studies of the trapping efficiency (per high energy positron incident on the crystal and trap) which are independent from source optimization (e.g., to minimize the active source area and to minimize self-

absorption). We are able to insert and remove intense sources from a well-shielded location at 4.2 K, without otherwise disturbing the accumulator. Without the use of any focusing elements, the strong magnetic field guides the high energy positrons along curving magnetic field lines through small (1 mm diameter) apertures, though this involves some losses. The separation of source and trap also provides space to mechanically chop the beam of high energy positrons. This enables direct lock-in detection of the tiny positron current that strikes a 110 face of a tungsten crystal that functions as a “reflection moderator” [9]. We measure up to  $3 \times 10^6$  positrons per second striking the crystal at 4.2 K. Unfortunately, a penalty for separating source and trap is also extracted, because the magnetic field increases from 1.9 T (at the source) to 5.9 T (at the crystal and trap). The increasing field helpfully compresses the beam area, but unhelpfully acts as a “magnetic mirror” that bounces most positrons back toward the source (because they adiabatically transfer all the energy in their motion toward the trap into cyclotron energy).

When crystal moderators are used at higher temperatures [9], between  $10^{-4}$  and  $10^{-3}$  of the incident positrons thermalize within the crystal, diffuse back to the entrance surface, and are ejected by the work function potential into a “beam” with a sub-eV distribution of energies. Some experiments [20,21] indicate that the narrow energy width (for motion perpendicular to the crystal) decreases with temperature, to  $<65$  meV for a 20 K crystal [20]. However, a conflicting report [22] indicates that quantum reflection largely prevents thermalized positrons from reemerging from a cold crystal. The contradictory observations, and our observation of cooled positrons emitted from a 4.2 K crystal, may be due to differences in crystal preparation. Preparation requirements are not yet well understood, except that a pure crystal with a clean, ordered surface is crucial to avoid losing positrons at defects, surface imperfections, and contaminants [9].

Our crystal face was mechanically polished to a mirror finish, and electrochemically etched to remove  $10 \mu\text{m}$ . It was then annealed at 2200 K and  $10^{-8}$  Torr for 4 h, kept at 1000 K in  $10^{-6}$  Torr of oxygen for 4 h (in the hope of removing interstitial carbon near the surface), then heated briefly to 2200 K at  $10^{-8}$  Torr. Within 2 h the crystal was attached to the Penning trap, and its enclosure was evacuated and cooled, reaching 4.2 K within 24 h. The crystal was suspended from four  $70 \mu\text{m}$  tungsten wires to thermally isolate it. This allowed a brief heating of the moderator by electron bombardment to as high as 2000 K while its surroundings were at 4.2 K. The heating preparation narrows the positron energy distribution and increases the emission rate as illustrated in Fig. 1. Unfortunately, the electron sources did not survive well at 4.2 K and 5.9 T. This kept us from optimizing the *in situ* preparation of the crystal, and from investigating steady-state crystal temperatures above 4.2 K.

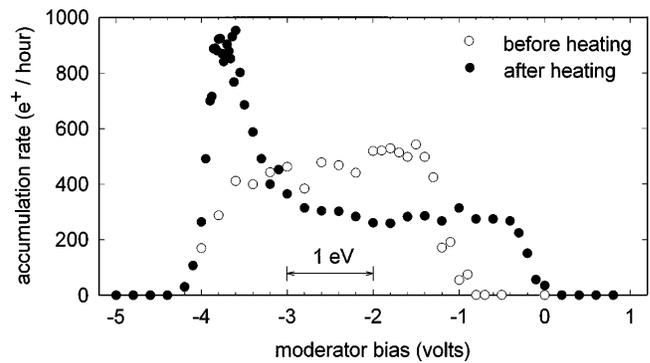


FIG. 1. Positron trapping rate vs energy of the slowed positrons measured before and after the moderator was heated to  $\sim 1600$  K *in situ* for 3 min.

The crystal is biased with respect to the trap electrodes to slow the eV positrons essentially to rest as they enter the trap. A conventional hyperbolic Penning trap (except for an “orthogonalized” geometry [23]) is biased so a positron within the trap will oscillate harmonically along the magnetic field direction at a frequency of 69 MHz. This “axial motion” induces a current in an attached *LCR* circuit which is resonant at the same frequency. The voltage across the circuit reveals the number of trapped particles. Power dissipated in the circuit damps the axial motion of a positron at the center of the trap at a rate  $\gamma_z = 2\pi(6.1)$  Hz, which is measured directly from the coherent response of fewer than 10 trapped electrons. The trap electrodes are coated with colloidal carbon to minimize the surface patch effects that are important when positrons oscillate near the electrode surfaces.

The weak electrical damping does not remove enough energy to keep a significant number of positrons from leaving through the entrance aperture after one axial oscillation in the trap. The solution [13,14] is to displace the entrance aperture 3.6 mm from the trap axis [Fig. 2(a)]. This ensures that positrons drift radially (in what is often called  $\mathbf{E} \times \mathbf{B}$  drift, or “magnetron motion”) by  $5 \mu\text{m}$  during one

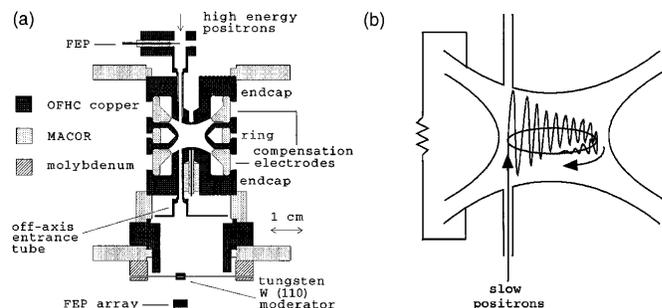


FIG. 2. (a) Penning trap and moderator for trapping of positrons. (b) Exaggerated view of the trajectory of a slow positron which enters the trap, and makes axial (vertical) oscillations of decreasing amplitude (due to the electrical damping) as the positron circles in a magnetron orbit. Small cyclotron orbits are not visible.

axial oscillation. Some positrons thus return to the aperture displaced farther from the local potential minimum on the aperture's axis, taking them as much as 0.3 meV up a small potential hill. Positrons with insufficient energy to overcome this potential barrier remain trapped for not only one axial oscillation, but also for one complete magnetron orbit about the central axis of the trap [Fig. 2(b)]. This extends the time for electrical damping by 500, allowing damping at a rate of  $\gamma_z$  to dissipate 28 meV of axial energy before a positron returns to the aperture. Positrons which remain trapped continue to dissipate energy in the circuit until they come into equilibrium with the tuned circuit near 4.2 K. The tiny 28 meV energy acceptance underscores the need for a comparably narrow spread in the cooled positrons entering the trap. Moreover, it makes it possible to analyze the energy spread of positrons entering the trap to high resolution (e.g., in Fig. 1).

Positrons are initially captured and damped into the large magnetron orbit with a 3.6 mm radius which has been mentioned. Positive ions are kept from loading simultaneously by strongly and resonantly driving their axial motions. After accumulating for a few minutes to a few hours, positrons are moved radially to the center of the trap via magnetron sideband cooling [24]. Centered positrons modify the measured Lorentzian line shape of the noise power across the *LCR* circuit in a familiar way [25] as illustrated by the frequency spectrum in Fig. 3(a). The width of the dip increases with the number of trapped positrons. Fitting the line shape reveals the number of trapped positrons, with a reproducibility of 1% and an accuracy of 10% (for thousands of positrons).

Figure 3(b) shows a 56 h accumulation in which positrons were moved to the center of the trap and counted every 4 h. Accumulation proceeded at a constant rate until  $3.5 \times 10^4$  positrons were trapped. This accumulation rate is slightly smaller than the largest observed rate of  $1.2 \times 10^3 e^+/h$ , which corresponds to nearly  $10^6 e^+/month$ . However, longer accumulation has not yet been investigated since larger numbers of trapped positrons produce large space-charge shifts in the effective trapping potential, shifting the positrons' axial frequency out of resonance with the *LCR* circuit. Subsequent studies with electrons suggest that such shifts can be managed.

Experimental tests which become possible with slowed positrons clearly establish the purely electronic damping [11]. Figure 4 shows how the loading rate peaks as the trap potential is tuned so a positron's axial frequency goes through resonance with the damping circuit. When the trap is optimally tuned (by tuning the potential applied to compensation electrodes), the sharp center peak is observed. Detuning the compensation potential to either side of the optimum produces the broadened resonances to either side. A small positron accumulation rate of  $5e^+/h$ , more comparable to that observed in the earlier experiment [13,14], remains even far off resonance where the electronic accumulation is no longer

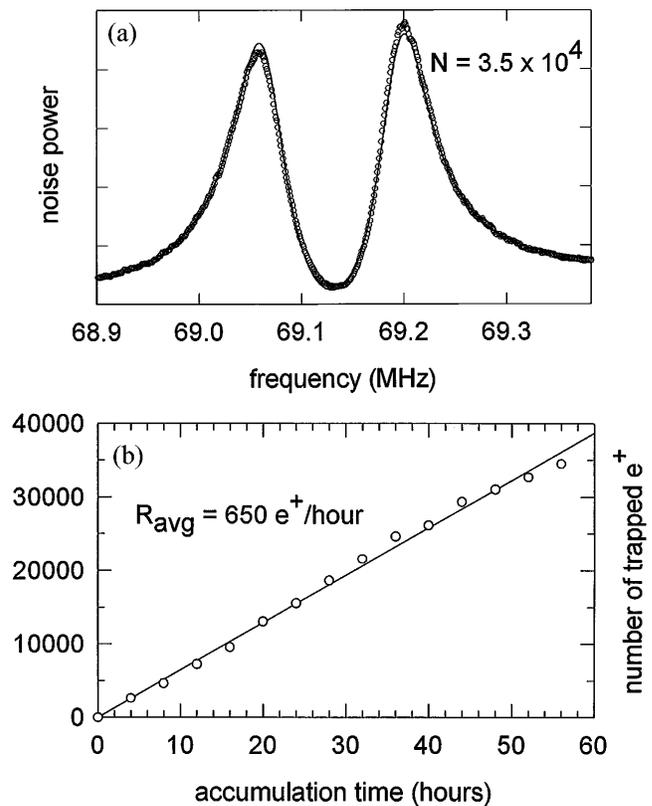


FIG. 3. (a) Measured noise spectrum across the *LCR* damping circuit (dots) and the fit (line) used to determine the number of trapped positrons. (b) Number of trapped positrons vs accumulation time.

effective. At optimum, the damping rate (deduced from the measured linewidths as in Fig. 4) is still 4 times lower than is measured for a particle centered in the trap, presumably because of imperfections in the potential near the electrodes. The maximum observed accumulation rate, per high energy positron incident on the crystal, then agrees with the calculated loading rate if  $4 \times 10^{-4}$  of the incident positrons emerge from the crystal in the low energy distribution.

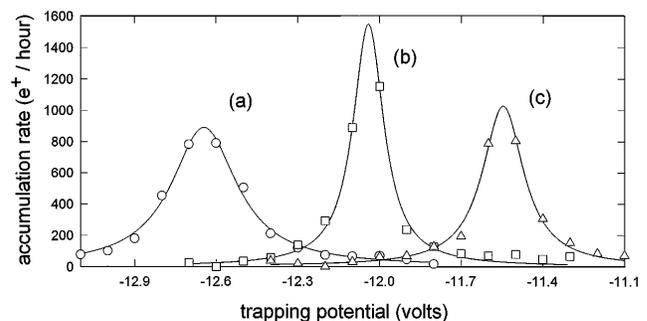


FIG. 4. Measured accumulation rate as a function of the trapping potential for a well tuned trap (i.e., harmonic axial motion from end cap to end cap) in (b), and for a mistuned trap (i.e., anharmonic motion) in (a) and (c).

Positron accumulation is thus sufficiently well understood so that possible improvements can be reasonably estimated. The accumulation rate would increase by more than a factor of 10 if the highest reported moderation efficiency and narrowest reported energy width were achieved, as should be possible with purer crystals prepared more carefully *in situ*. An additional factor of 7 in loading rate could be gained by moving the radioactive source into the high field near the trap to eliminate the magnetic mirror. This would also require increasing the trap apertures to match the source area, may thus require more trap tuning to offset the increased anharmonicity, and may be most practical with a transmission moderator [9]. Since the  $^{22}\text{Na}$  source was initially near the limit imposed by self-absorption, the activity of this source could only be increased by a factor of 2 in the current configuration. Alternatively, a more intense source with a shorter half-life could be used. For antihydrogen production at CERN, it now looks practical to use a  $^{19}\text{Ne}$  source (half-life of 17 s) with an activity greater than 1 Ci [26]. A more intense source and moderator could also be placed outside of the strong magnetic field and the beam focused onto a remoderator near the trap. There are also plans to cool slowed positrons by collisions with laser-cooled ions [27].

There is little to add to the extensive speculation about antihydrogen production [5] beyond that cold trapped positrons and antiprotons are now available for the first time in ultrahigh vacuum, at densities of  $10^8/\text{cm}^3$ . Our recombination studies underway with electrons and protons suggest it is clearly desirable to increase the number of cold positrons to perhaps  $10^5$  or  $10^6$ . However,  $4 \times 10^4$  cold positrons are already sufficient to cool highly stripped ions in a trap, with more positrons increasing the cooling rate. Positron cooling of ions will work just like the electron cooling of antiprotons [28], demonstrated to reduce the energy of keV antiprotons by more than 7 orders of magnitude [1,8]. Positrons in a high magnetic field cool rapidly by radiating synchrotron radiation (unlike protons or other heavy particles), and highly stripped ions will not charge exchange with background gas (due to the high vacuum).

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