Field Ionization of Strongly Magnetized Rydberg Positronium: A New Physical Mechanism for Positron Accumulation

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Magnetized Rydberg positronium forms when an energetic positron (e^+) slows within a tungsten crystal and picks up an electron (e^-) as it emerges in a strong magnetic field. The signature is equal numbers of e^+ and e^- when a weak electric field is applied, either of which can be accumulated and counted. The new e^+ accumulation technique is simple, robust, and much more efficient than any other demonstrated to be compatible with a cryogenic vacuum. Possible applications include the study of cold single component plasmas of e^+ and the formation of cold antihydrogen.

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A cold plasma of positrons, confined in a region free of gas atoms, offers exciting research opportunities. Losses could be precisely monitored, and even spatially imaged, using the photons from e^+ annihilation. A sufficiently dense plasma, interacting with cold antiprotons, could lead to the production and precise laser spectroscopy of cold antihydrogen. It is well established that a fraction of the energetic e^+ from a radioactive source, if sent into a crystal, will emerge with eV energies [1]. However, it is difficult to find an efficient physical mechanism which can slow even these low energy e^+ rapidly enough to confine them in a nearly ideal vacuum. The challenge is that a charged particle by itself cannot travel into a trap and be captured. If it has enough energy to get into a region where conservative forces would confine it, it has enough energy to get out. Even a slow 1 meV e^+ travels 1 cm, the typical length of a trap, in only 0.5 μs. The required physical mechanism must remove sufficient kinetic energy on this time scale to allow the e^+ to be trapped.

In this Letter we demonstrate a new physical mechanism for capturing cold positrons in a nearly ideal vacuum. We form strongly magnetized Rydberg positronium (which may itself be useful for antihydrogen production) and ionize it using a weak electric field within a Penning trap. The accumulation rate is orders of magnitude higher than was attained by electronically damping positrons passing through the trap [2,3]. Positrons are accumulated directly into an exceptionally high vacuum, with the density of background gas atoms shown to be less than 100 cm^{-3} in a similar apparatus [4]. This is a pressure more than 10 orders of magnitude lower than used to initially capture positrons via collisional damping [5], an approach not yet demonstrated to be compatible with the cryogenic vacuum. As a e^+ accumulation method, the new approach is simple, efficient, and robust. An early version allowed simultaneous confinement of the ingredients of cold antihydrogen in a cryogenic vacuum [6]. The new physical mechanism is also unusual and extremely interesting in its own right; the only previously observed nonresonant formation of positronium (Ps) was for low excited states [1] (though resonant excitation from $n = 2$ to $n = 15$ has been reported [7]).

Figure 1a shows the simplicity of the apparatus. A thin transmission moderator, a 2 μm tungsten crystal W(100), is added to an open access Penning trap [8] at one end. A thick reflection moderator, a 2 mm tungsten crystal W(110), is added at the other. Positrons from a radioactive source (2.5 mCi ^{22}Na with a 2 mm diameter), traveling along field lines of a strong magnetic field (5.3 T), pass through the transmission moderator to enter the trap. They accumulate in the location shown.

Both the thin transmission moderator crystal and the highly polished reflection moderator crystal were treated using standard techniques [9]. They were heated by an electron beam to 1200 °C in 10^{-6} Torr of oxygen for 30 min and then held at 2000 °C for 3 min in a vacuum better than 10^{-7} Torr. After five repetitions the moderators were slowly cooled to room temperature, exposed to 1 Torr of oxygen, then placed into our apparatus. Both moderators were exposed to air for at least three days

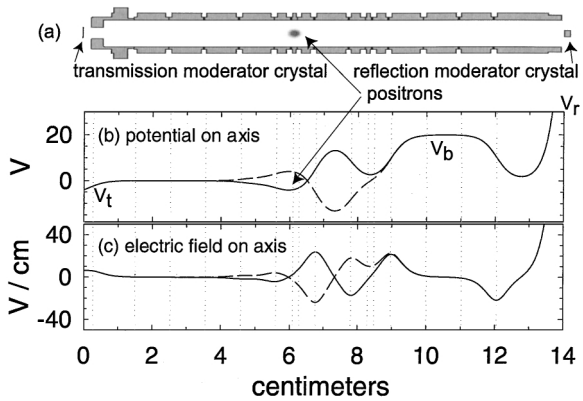

FIG. 1. The electrodes of an open access Penning trap (a) are biased to produce an electric potential (b) and field (c) along the central axis that confines e^+ (solid curves) or e^- (dashed curves). A 5.3 T magnetic field parallel to this symmetry axis guides fast positrons entering from the left through the thin crystal and towards the thick crystal.

before the apparatus was evacuated. The transmission moderator is suspended from four 70 μm tungsten wires to thermally isolate it.

The potentials and electric fields used to accumulate e^+ (solid curves in Figs. 1b and 1c) are produced by separately biasing the stack of coaxial, gold-plated, copper ring electrodes. Electrons are accumulated at the same location when the potential in the trapping region is reversed in sign (dashed curves in Figs. 1b and 1c). The trap is completely surrounded by an evacuated copper enclosure kept at 4.2 K via thermal contact to liquid helium. The energetic e^+ from the source pass through a shutter which either blocks them or allows them to enter the enclosure through a 10 μm Ti window. A 2 pA e^+ current is measured on the transmission moderator.

A nondestructive measure of the number of accumulated e^+ or e^-, equally efficient for both species, comes from the Johnson noise spectrum across an *RLC* circuit attached to the trap electrodes. For an empty trap, the measured frequency spectrum is a Lorentzian centered at the circuit's resonant frequency (e.g., central peak in Fig. 2a). The harmonic oscillation of trapped particles along the magnetic field direction shorts the Johnson noise at the resonant frequency of the particles. The single peak splits into two, with a frequency spacing (e.g., Fig. 2a) that grows with the number of trapped particles in a well understood way [10]. Figure 2b shows the accumulation of more than a million positrons.

The new physical mechanism for accumulating positrons takes place one e^+ at a time; it does not depend upon the interaction of successive e^+ from the source. The most direct evidence is that the number of accumulated e^+ is proportional to the incident flux of e^+ from the radioactive source. This flux is deduced from the current measured on the reflection moderator and is varied by pulling the radioactive source away from the trap.

The strong magnetic field is crucial to the new physical mechanism. It keeps the "guiding center" [11] of any slowed e^+ or e^- that emerges from the transmission moderator on a magnetic field line as it passes through the trap. The tiny magnetic moment associated with a small radius cyclotron orbit about the guiding center has a negligible effect on the trajectories. Such a moment is an adiabatic invariant. Since the magnetic field is homogeneous, the magnetic moment and the cyclotron energy to which it is proportional are essentially constant (except for radiation damping) and uncoupled from the axial motion. The electric fields of the trap (or from a partner particle of order 1 μm away) will accelerate or decelerate a charged particle along its magnetic field line. These electric fields are not strong enough to allow $\vec{E} \times \vec{B}$ drift motion to move the particle appreciably off its one dimensional axial field line path during one pass through the trap.

The new physical mechanism for capturing positrons arises when a moderated positron leaves the transmission moderator followed by a secondary electron. (As mentioned, an e^+ cannot travel into the trap by itself and be captured.) The strong magnetic field keeps the e^+ and e^- on nearby field lines. Biasing the transmission moderator to potential V_t with respect to neighboring electrodes adds energy eV_t to one species and removes eV_t from the other. Optimizing V_t (Fig. 3a) thus reduces the axial spacing between e^+ and e^- and improves their axial velocity matching as they approach the potential well of the trap. If their Coulomb attraction energy exceeds their kinetic energy in the center-of-mass frame they are bound in a highly magnetized state of Rydberg positronium. This positronium is polarized and then ionized by the electric field within the trapping well if this field is strong enough. If the kinetic energy of the e^+ is sufficiently low it will be captured, while the e^- carries off the excess energy.

A distinct signature of this new physical mechanism is that the rates for accumulating e^+ and e^- should be the same. Positrons are captured in the potential well represented by the solid curve in Fig. 1b. Inverting only the well potential (dashed curve in Fig. 1b) instead confines e^-. The striking equality of the superimposed accumulation rates in Figs. 3a, 4a, and 4b for positrons (filled circles) and electrons (open circles) provides the

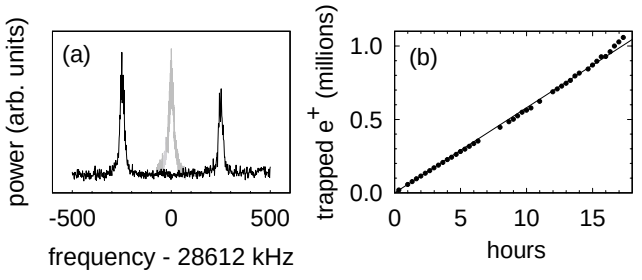

FIG. 2. More than 1×10^6 positrons, measured nondestructively using the Johnson noise detection described in the text (a), are accumulated in 17 h (b).

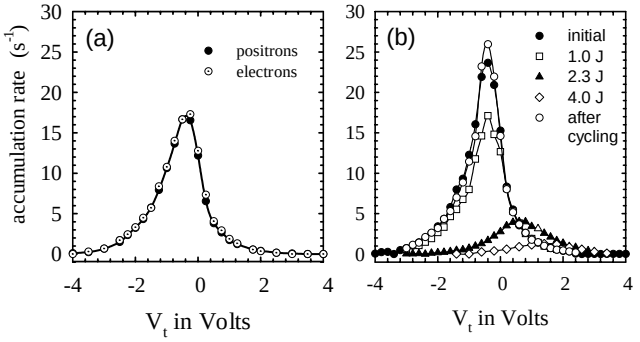

FIG. 3. (a) Accumulation rates, strikingly equal for positrons and electrons, depend upon the potential of the transmission moderator, and hence upon the electric field at the moderator surface. (b) Changes in positron accumulation rate when adsorbates on the transmission moderator surfaces are desorbed using laser pulses (100 ms of 818 nm with a 20% duty cycle) with the total energy indicated. The cycling is to 300 K then back to 4.2 K.

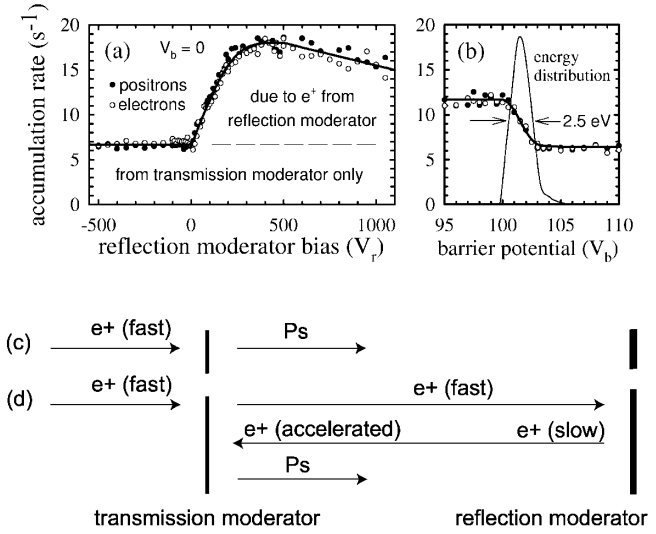

FIG. 4. (a) Increasing the potential V_r of the reflection moderator opens a second channel for e^+ accumulation by allowing nearly monoenergetic e^+ to return to the transmission moderator. (b) Increasing the potential barrier V_b above $V_r = 100$ V first shows that these e^+ have an average energy of 1.5 eV and a 2.5 eV width, then blocks the returning e^+ to stop the additional accumulation. The two channels to Ps formation and e^+ accumulation are represented in (c) and (d).

confirming evidence. The rates depend identically upon the trap potentials which are not inverted—the transmission moderator potential V_t (Fig. 3a), the reflection moderator potential V_r (Fig. 4a), and the barrier potential V_b (Fig. 4b).

As a further test that positronium enters the trap, we raise the potential between the transmission moderator and the trapping well by up to 6 V so that one of the charged species by itself could not enter the trap well at all. The potential changes gradually enough as a function of position that the electric field does not increase significantly. If the loading mechanism does not involve neutral positronium this would essentially eliminate the accumulation. It does not.

The positronium that is ionized must be in a high Rydberg state, with positron and electron well separated, insofar as the weak electric field of the Penning trap (Fig. 1c) is sufficient to accomplish the ionization. Figure 5 shows the accumulation rate as a function of the magnitude of the maximum axial electric field within the Penning trap. The electric field E_z necessary to counter the attraction of the e^+ and e^-, spaced by r, is $E_z = 14(\mu\text{m}/r)^2$ V/cm in the simplest linear model, neglecting the kinetic energies. In this model, most of the positronium ionized thus seems to have e^+ and e^- spaced by $1-5$ μm. As the electric field in the trap well is increased farther than shown in the figure, the accumulation rate begins to drop slightly, presumably because the electric field starts to influence the tuning of the relative velocity previously optimized by changing V_t and more field ionization takes place before the trapping well.

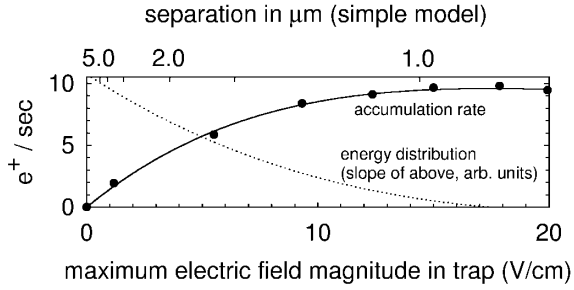

FIG. 5. Measured dependence of accumulation rate upon the maximum electric field magnitude within the confines of the Penning trap (points) and deduced shape of the ionization energy of the Rydberg positronium (dotted curve).

The formation of the ground state and lowest excited states of positronium at the surface of crystal moderators is well known [12] and becomes more efficient when the moderator is heated [13]. Stabilization of large-orbit positronium in a strong magnetic field is also predicted [14]. However, field-assisted formation of Rydberg positronium from a cold surface has yet to be theoretically investigated.

The magnetized Rydberg positronium that we have been discussing is formed via two distinguishable channels that are represented in Figs. 4c and 4d. The first channel (Fig. 4c) is most direct. An energetic e^+ from the radioactive source slows in the transmission moderator, from which it emerges accompanied by a secondary electron and is ionized as described above.

The second channel opens when nearly monochromatic e^+, with much lower energy than that of the e^+ from the source, are directed back to the transmission moderator. Figure 4a shows a sharp increase in the e^+ and e^- accumulation rates, which more than double when the potential V_r on the reflection moderator is raised to allow the return. Figure 4b gives direct evidence of these low energy e^+ for $V_r = 100$ V. Varying the height of a potential barrier V_b placed in their path shows them to be positrons moderated in the thick reflection moderator, with an average kinetic energy of 1.5 eV and an energy width of 2.5 eV. Most incident e^+ from the source emerge from the thin transmission moderator crystal with enough energy to pass through the trap and strike the thick moderator. A fraction $\eta_r \approx 10^{-3}$ of these slow and diffuse near the entrance surface of this crystal, then emerge with low energies [1]. Upon returning to and entering the transmission moderator some fraction of the backward traveling positrons are slowed in the transmission moderator and emerge accompanied by a secondary electron just as for the first channel. Above $V_r = 400$ V the accumulation rate gradually decreases, presumably because an accelerated e^+ penetrates deeply enough into the transmission moderator to be less likely to diffuse near the crystal surface and emerge with a secondary electron.

The formation rate for Rydberg positronium depends upon the gas adsorbed on the surface of the transmission

moderator, perhaps because the gas modifies the work functions or the secondary electron emission. We gradually remove the gas layer with 100 ms pulses of up to 4 W of 818 nm radiation (with a 20% duty cycle) from a laser diode, while the trap remained at 4.2 K. Figure 3b shows the resulting decrease in the e^+ accumulation rate. The peak in the accumulation rate also shifts to a value of the transmission moderator potential V_t that is higher by 2 V. The adsorbed gas layer and higher accumulation rate are restored when the trap and its vacuum container are simply warmed to 300 K and then cooled back to 4.2 K. The restored accumulation rate is slightly larger than initially observed. We observed similar changes in e^+ efficiency when we used antiprotons and electron-beam heating to remove absorbed gas [6]. Nonetheless, over months of loading and repeated cycling of the apparatus between 300 and 4 K, the peak loading rate remains stable as long as the adsorbed gas is not deliberately removed from the surface of the transmission moderator crystal.

The peak loading rate we observed was 4×10^4 $(e^+/\text{hr})/\text{mCi}$. This corresponds to 2×10^{-6} trapped e^+ per high energy e^+ incident on the transmission moderator, as deduced from the current on the reflection moderator. (This would be 0.2% of the number of slowed e^+ leaving the moderators if $\eta_t = \eta_r = 10^{-3}$ of the e^+ from the source emerge after being thermalized.) Improved rates for the production of Rydberg positronium and the accumulation of cold e^+ seem possible. The most straightforward increase would come with a larger radioactive source. For example, a 150 mCi ^{22}Na source (the largest available commercially in a compatible size) should increase the rates by a factor of 60, so that a million e^+ should be accumulated in 12 min. Increasing the efficiency η_r for slowed positrons ejected from the reflection moderator, by covering the reflection moderator with neon [15], could improve the accumulation rate by more than an order of magnitude, provided that an insulating layer of neon would not be allowed on the trap electrodes.

In conclusion, highly magnetized Rydberg positronium is formed when fast positrons from a radioactive source slow and pick up electrons from tungsten crystals in the presence of a strong magnetic field. With the application of appropriate electric fields, the Rydberg positronium is ionized. Either the positrons or the electrons can be accumulated by choosing the sign of the potential well. Equal accumulation rates for positrons and electrons give evidence that their source is positronium, and only Rydberg states could be ionized with the weak electric field that is used. The dependence of the accumulation rates upon the applied electric fields are presented to stimulate the development of detailed production models. As a positron accumulation method, the new technique is efficient, robust, and compatible with a cryogenic vacuum.

Many applications are envisioned. For antihydrogen production, the Rydberg positronium has a large cross section [16] in collisions with antiprotons to form antihydrogen directly. Cold plasmas of pure positrons could be mixed with pure antiprotons to produce antihydrogen that is cold enough to be magnetically confined for precise spectroscopy measurements. The pure positron plasma in a cryogenic vacuum could also be used as a cooling fluid for highly stripped ions [3], just as electrons are used to cool energetic antiprotons [17], without fear of charge exchange. Finally, a cold single-component plasma of positrons offers the unusual possibility to image losses spatially with a suitable annihilation detector.

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