Electron Cooling of Protons in a Nested Penning Trap

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Trapped protons cool via collisions with trapped electrons at 4 K. This first demonstration of sympathetic cooling by trapped species of opposite sign of charge utilizes a nested Penning trap. The demonstrated interaction of electrons and protons at very low relative velocities, where recombination is predicted to be most rapid, indicates that this may be a route towards the study of low temperature recombination. The production of cold antihydrogen is of particular interest, and electron cooling of highly stripped ions may also be possible. [S0031-9007(96)01109-X]

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Interesting features of low temperature recombination processes have been calculated but not yet explored experimentally. For example, the rate for three body recombination of antiprotons ($\bar{p}$) and positrons (e^+) to form antihydrogen ($\bar{\mathrm{H}}$),

$$\bar{p} + e^+ + e^+ \rightarrow \bar{\mathrm{H}} + e^+, \quad (1)$$

is predicted to increase by up to 8 orders of magnitude when the temperature of interacting antiproton and positron plasmas decreases from 300 to 4.2 K [1–3]. The recombination of antihydrogen is of great interest [4], especially if the antihydrogen would be cold enough to be trapped for precise laser spectroscopy (as recently demonstrated with cold, trapped hydrogen [5]) or for gravitational studies [6,7]. Cold charged particles for recombination experiments have been confined in recent years in Penning traps at 4.2 K, even 10^5 antiprotons [8] and 10^6 positrons [9] (in separate experiments) for antihydrogen. Cold electrons, protons, and positive ions are even more readily available, of course, so that recombination to form hydrogen, positronium, and various positive ions (from more highly stripped ions that capture electrons) can be contemplated as well. The major obstacle which has so far prevented such low temperature recombination studies is the difficulty of making cold trapped particles of opposite sign to interact at low relative velocity.

In this Letter we demonstrate the electron cooling of trapped protons, the first time that such "sympathetic" cooling is observed with simultaneously trapped particles of opposite sign. In a nested Penning trap, collisional cooling continues until the initially hot protons reach a very low velocity relative to the cold electrons. This establishes the nested Penning trap as a promising environment for the study of low temperature recombination. After cooling, the interaction of the protons and electrons can be controlled by adjusting potentials. The good control may even make it possible to cool highly stripped positive ions via collisions with cold electrons, by arranging that the ions and electrons decouple after the ions cool but before they recombine. The demonstration is carried out within a cryogenic apparatus whose interior vacuum is already low enough to avoid the annihilation of antihydrogen. (A pressure below 5×10^{-17} Torr has been demonstrated in a similar apparatus [8].)

The nested Penning trap has some advantages over two possible alternatives, even though in principle these alternatives permit oppositely charged species to interact continuously at the lowest energy that can be attained. As reported recently in this journal [10], hot positive ions in a Penning trap have been simultaneously confined with hot electrons in a superimposed Paul trap. Presumably this demonstration could eventually be done with cold protons and electrons in a low temperature apparatus, without contaminant ions. The serious challenge is that the microwave driving force which trapped the electrons also heated them enough to drive ions out of the trap via collisions. Such "micromotion" heating would also be a major problem for the second alternative, large numbers of particles of opposite sign confined together in a Paul trap. In this case, species with very different masses (e.g., $\bar{p}$ and e^+) would also be confined with forces of very different strengths.

Since the nested Penning trap was suggested [1], its use has allowed ion cyclotron resonance spectroscopy of oppositely charged ions [11,12] along with the preliminary studies (with helium ions and electrons) that led to this work [13]. In the form used here, the nested Penning trap is an outer potential well for protons, within which is nested an inverted well for electrons [Fig. 1(b)]. The wells are generated by applying potentials to a stack of cylindrical ring electrodes made of gold-plated copper, with inner surfaces shown (to scale) in Fig. 1(a). (The design and operation of such "open-access" traps has been discussed [14].) Electrode potentials up to ± 150 V are derived from a computer-controlled DAC which is amplified by high voltage op-amps and heavily filtered (0.1 s time constant), making it possible to remotely change the potentials as needed to load and move the electrons and protons into desired locations. A 6 T magnetic field is directed along the symmetry axis of the trap. Figure 1(b) is the potential along the center axis of the trap; the axial potential wells are slightly deeper just off this axis.

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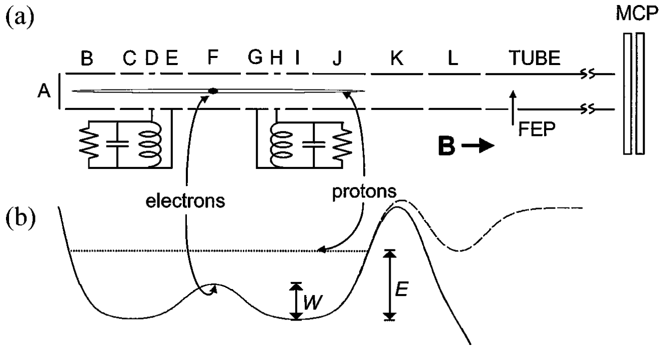

FIG. 1. Scale outline of the inner surface of the electrodes (a), and the potential wells (b), for the nested Penning trap.

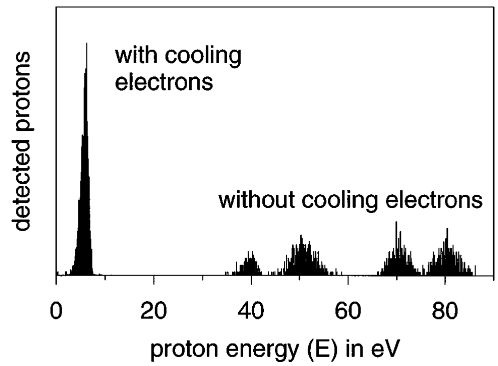

FIG. 2. Energy spectrum of the hot protons (right) and the cooled protons (left), obtained by ramping the potential on electrode K downward and counting the protons that spill out to the channel plate. The hot and cooled spectra for 4 initial proton energies are summed. The electron well depth is $W = 7.4$ V.

Particles released from the trap follow field lines of the superconducting solenoid until they strike a chevron pair of 25 mm diameter microchannel plates (MCP) located 34 cm to the right of electrode K. This separation puts the MCP in the 0.5 T fringing field of the superconducting solenoid, away from the 6 T field at the trap which would seriously impair MCP performance. It also allows operation of MCP at 40 to 50 K to shorten the recharge time for the channels [15]. The measured detection efficiencies for protons accelerated to 3 keV and electrons accelerated to 1 keV are consistent with the 66% open area of the channels.

Between 1 and 10^4 protons are loaded into the trap as a result of a 40 nA, 1.1 keV electron beam from a field emission point (FEP). The electrons travel through the trap along a magnetic field line [from right to left in Fig. 1(a)] to strike electrode A. Hydrogen dislodged from this electrode can be ionized while it drifts through the electron beam, and captured in the well formed with electrodes G, H, and I. A strong noise source with a carefully shaped frequency spectrum is applied to the electrodes of this well to expel other positive ions, a procedure shown to be effective in experiments which require that a single trapped proton be well separated from all contaminant ions. The protons are detected and counted nondestructively while they are centered within electrode H by observing their interaction with a circuit connected to electrode G. The *RLC* circuit is resonant with their oscillatory motion along the direction of the magnetic field. Contaminant ions are no longer observed after the noise is applied, indicating that they have been expelled from the trap or at least from the central region where the rest of the experiment takes place. Next, the protons are transferred to a well just to the right of the nested Penning trap [dotted potential well centered on electrode L in Fig. 1(b)]. This well is raised or lowered to choose the injection energy of the protons with respect to the bottom of the nested trap. The protons are then released into the outer well by lowering the potential applied to electrode K for 1 s.

With no electrons in the inner well of the nested trap, the protons maintain the energy with which they were loaded into the outer well. The energy spectrum for four separate injections of protons, each at a different injection energy, are summed to the right in Fig. 2. These energy distributions are measured by adiabatically ramping down the potential on electrode K. The 125 V applied potential is ramped exponentially to -10 V with a time constant of 0.1 s. A proton in the outer well with energy E escapes the trap and travels to the MCP when this potential is reduced to some $V(E)$. Generally $V(E) = E$, but a small correction to this equality must be made to account for the adiabatic cooling that takes place when the depth of the proton's confining well is reduced. We deduce the small correction by integrating the equation of motion for a proton moving on axis while the potential is changing. The number of escaping particles is plotted versus their energy E in Fig. 2. Evaporative cooling is neglected because the number of trapped particles is small, their density is low, and the potential is ramped relatively quickly.

Cold electrons can be confined in the inner well (centered on electrode F) before introducing protons into the outer well of the nested trap. These electrons also are generated by the electron beam described above, and cool to equilibrium with their 4 K environment via synchrotron radiation, with a 0.1 s time constant. Their number is measured by observing the way they modify the noise resonance of a *RLC* circuit attached to electrode D. The cooling examples shown involved 3×10^5 trapped electrons.

With 4 K electrons in the inner well, hot protons introduced into the outer well cool dramatically within several seconds. The energy spectrum of the cooled protons (for an electron well depth $W = 7.4$ V) is the taller peak to the left in Fig. 2. This peak is the sum of spectra of four separate injections of hot protons into the outer well, under conditions identical (except for the lack of cold electrons) to the four previously described injections. Whatever the initial energy and energy spread of the injected protons, the electron cooling yields the same cooled energy distribution. Approximately 60% of the cooled protons escape to the MCP when the potential on electrode K is reduced. These include the protons confined in the right side of the outer well, without sufficient energy to pass through the trapped electrons, along with protons with just enough energy to continue passing through. The remaining 40% of the cooled protons are confined in the outer well to the left of the electrons. These are later sent to the MCP and counted, but it is more difficult to measure their energy spectrum accurately. The spectra in Fig. 2 are normalized so that equal numbers of counts are in the hot and cold spectra, to compensate for the 40% of the protons trapped to the left of the electrons, and for fluctuations in the number of initially injected protons.

The cooled protons have a very low relative velocity with respect to the cold electrons. To demonstrate this, we repeat the cooling described above for different depths of the inner electron well W. The space charge potential of the small number of trapped electrons is only of order 10^{-1} V, so that protons cooled to a low relative velocity with respect to the electrons should thus have energy $E \approx W$. (Lower energy protons with $E < W$ are unable to climb the potential hill to interact with the electrons.) This proportionality is demonstrated in Fig. 3. A low relative velocity between trapped species of opposite sign offers the possibility to study recombination processes under the conditions where the rates are highest.

The width of the cooled proton spectrum is intriguing but not yet well studied and understood. While the phase space compression (compared to the hot spectra) is clear, the cooled proton peak is still much wider than one could expect for a small number of 4 K protons. One possible explanation is that the potential energy in the Coulomb repulsion of the protons makes the width of the observed peak depend on the number of cooled protons. In a similar apparatus, widths below 10 meV were observed but only for very small numbers of cooled antiprotons [8]. The cooled proton peak could also be broadened by the radial ("magnetron") distribution of the protons, insofar as the depth of the trapping potential well increases off the central axis of the trap. A third possible explanation for the width is three body recombination to form hydrogen, the matter counterpart of the process in Eq. (1). Hydrogen atoms formed by this process would be initially in high Rydberg states, with energy corresponding to principal quantum numbers $n > 100$. Such hydrogen would be ionized by the electric fields >7 V/cm of the Penning trap. The protons and electrons would be recaptured in their respective wells, but with an energy width that depends upon where the hydrogen atoms were formed and ionized.

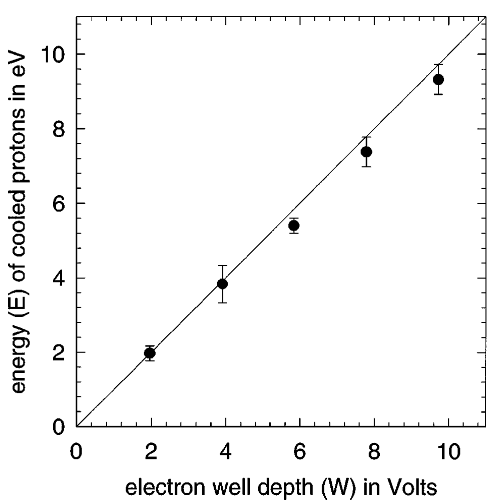

FIG. 3. Demonstration that hot protons cool until they have a low relative velocity with respect to the electrons. The energy (E) of the cooled protons is proportional to the depth of the electron well (W), both energies being measured with respect to the bottom of the right side well.

A nested Penning trap with shallower potential wells would avoid the ionization, and is thus an attractive environment to study the steep temperature dependence of the high predicted rates for three body recombination at low temperatures. Lower rate, radiative recombination [16] can also be studied in a nested Penning trap. One example is

$$\bar{p} + e^{+} \rightarrow \bar{\mathrm{H}} + h\nu\,. \qquad (2)$$

The potential wells would be made deep enough to deliberately ionize the high Rydberg atoms produced initially in the three body process, returning their constituents to their respective potential wells. The rate for radiative recombination of trapped constituents could be greatly increased with laser stimulation [17], which for antihydrogen is

$$\bar{p} + e^{+} + h\nu \rightarrow \bar{\mathrm{H}} + 2h\nu\,. \qquad (3)$$

Based upon a comparison of predicted recombination rates with trapped positrons and antiprotons [1], it should be possible to observe, study, and use each of these three processes. Interestingly, it will probably be possible to detect antihydrogen more directly and with greater sensitivity than other recombined atoms owing to the near unit detection efficiency for antiproton annihilation.

In conclusion, protons in the outer well of a nested Penning trap cool dramatically via collisions with 4 K electrons simultaneously confined in the nested trap's inverted inner well. This environment is attractive for the study of low temperature recombination processes, insofar as the protons cool to low velocities relative to the electrons, where recombination rates are expected to be highest. A nested Penning trap with shallow potential wells should allow the investigation of three body recombination rates that are predicted to increase by 10^8 between 300 and 4 K. A nested Penning trap with deeper potential wells should allow the study of radiative recombination and laser-stimulated radiative recombination, along with the possibility of efficient cooling of highly stripped ions and efficient positron accumulation. Sufficient numbers of cold trapped protons, antiprotons, electrons, positrons, and positive ions have been confined to allow study of recombination to form cold hydrogen, antihydrogen, positronium, and many positive ions in the new environment of a nested Penning trap. The recent observation of nine antihydrogen atoms [18] adds to an already strong interest in the recombination of antihydrogen [4]. Unfortunately, these atoms traveled much too fast to allow accurate measurement, even if large numbers of high energy antihydrogen atoms could be foreseen. The demonstrated, low temperature interaction of cold, trapped particles within a nested Penning trap bodes well for the production and study of cold antihydrogen, whose properties could be accurately compared to those of hydrogen.

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