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POSSIBLE ANTIHYDROGEN PRODUCTION USING TRAPPED PLASMAS

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Since antiprotons have been captured in an ion trap, we consider the possibility of producing antihydrogen by merging cold trapped plasmas of antiprotons and positrons. The calculated, instantaneous rate for antihydrogen production by the 3-body recombination $p^- + e^+ + e^+ \rightarrow \overline{H} + e^+$ is much higher than for other proposed techniques, opening up intriguing experimental possibilities.

Antiprotons were recently captured within the small volume ($\approx$ 10 cm^3) of an ion trap by the TRAP Collaboration [1]. They were decelerated from GeV production energies down to 21 MeV within the LEAR facility of CERN, passed through approximately 3 mm of beryllium to slow them below 3 keV, and caught in an ion trap for as long as 10 minutes. While this is a much shorter time than the 10 month confinement of a single electron in a Penning ion trap [2] prospects are now excellent for holding antiprotons much longer under improved vacuum conditions.

An exciting possibility raised by the capture of antiprotons in an ion trap is that of producing antihydrogen in this environment. Separately trapped plasmas of electrons, positrons and protons are routinely studied at 4.2 K, with lower temperatures possible. Here, we consider the antihydrogen production that results from merging cold plasmas of positrons and antiprotons [3]. The calculated rate is orders of magnitude higher than either the projected rate for merged beams of antiprotons and positrons in a storage ring [4,5] or for collisions between a positronium beam and trapped antiprotons [6].

With antihydrogen in thermal equilibrium below 4.2 K, intriguing experimental possibilities can be considered. It becomes energetically possible to confine the antihydrogen, because of its magnetic moment, in a minimum of a magnetic field as has been done with sodium atoms [7]. Since we began exploring this difficult scenario [8], spin polarized hydrogen atoms at 0.04 K have also been confined this way [9]. A deeper well may be required than has been used so far to confine atoms (a 1.5 Tesla well is needed to trap antihydrogen at 1 K, for example). The coldest atoms in the thermal distribution can of course be caught in a shallower well. In fact, a trap environment is now considered to be most promising for more precise laser spectroscopy of hydrogen atoms [10]. Comparisons of the fine and hyperfine structure of hydrogen and antihydrogen would provide extremely precise tests of CPT. If the antihydrogen atoms are confined, even a weak, monochromatic Ly α source may be useful for further cooling. With low enough atom temperatures, the gravitational force on antihydrogen can be measured since this force shifts the location of the atoms within the trap [11]. Although the gravitational force is very small and this shift has not yet been observed despite earlier indications [12], it should be possible to observe this effect with trapped Na atoms in the near future. Experimental probes of gravitation are scarce and there is current theoretical interest in possible scalar and vector contributions to gravity which would cancel for matter but not for antimatter [13].

We shall assume that it is possible to trap $N_{\mathrm{p}} = 10^4$ antiprotons. In the demonstration experiment [1] of order 10^3 antiprotons were captured from each burst of 10^8 antiprotons from LEAR. With higher trapping potentials, lower LEAR extraction energies and optimization of the loading process, an increase of an order of magnitude or two could be achieved. Antiproton cooling to 4.2 K was not attempted in our short trapping demonstration, but will be tried soon. For positrons, we assume that a density $n_{\mathrm{e}} = 10^7/\mathrm{cm}^3$ can be achieved. This positron density at 4.2 K has been nearly realized, but with only 100 positrons in a trap [14]. Many more positrons could be trapped if modern moderation techniques are used. Long half-life positron sources, involving no linac or reactor, are now available [15] which produce sub-eV positrons at a rate of 10^7/sec. The challenge is getting the positrons into the trap, since continuous sources are not well matched to trap loading. For electrons, where pulsed sources are routine, plasma densities as high as $10^{10}/\mathrm{cm}^3$ have been obtained [16]. Densities of positrons comparable to these would require using linac-driven positron sources [17] or the efficient bunching of intense radioactive sources.

At least two trapping configurations should permit two oppositely charged plasmas to overlap. A Paul radiofrequency trap confines particles via oscillatory fields and thus is able to simultaneously confine positrons and antiprotons in a single trap [18]. When such a trap is stable for positrons it is automatically stable for the heavier antiprotons as well. Simultaneous confinement of Tl^+ and I^- ions has been observed [19]. A nested pair of Penning traps (fig. 1) is the other trap configuration. It has some possible advantages. A strong (≈ 6 Tesla) magnetic field is responsible for radial confinement. Appropriate potentials on a series of cylindrical electrodes (fig. 1a), with axis in the direction of the magnetic field, produce two oppositely signed potential wells (fig. 1b). A central well which can be filled with positrons is nested within a surrounding second well for antiprotons. The central well for positrons is a potential hill for antiprotons. Antiprotons will be kept entirely out of the center region until the center hill is lowered enough to allow the antiprotons to oscillate through the positron cloud. The two

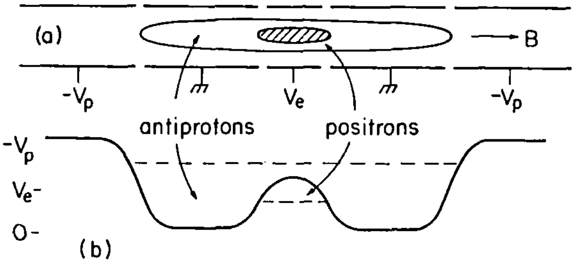

Fig. 1. Electrodes (1a) and axial potential (1b) for a nested pair of Penning traps.

plasmas can thus be kept separate for cooling and then merged at a definite time. For the rapid recombination process we will discuss, this should minimize possible centrifugal, radial separation [20] of the positron and antiproton plasmas since this happens at a much slower rate. Moreover, raising and lowering the depth of the central well allows some adjustment of the relative velocity between the plasmas. The recombination rates we shall discuss depend upon the relative velocity between antiprotons and positrons. With positrons at 4.2 K, the heavier antiprotons could have energies as high as 1 eV before the recombination rates are significantly modified. This allows the possibility of producing "beams" of antihydrogen exiting the ends of the trap by keeping the axial energy of the antiprotons substantially higher than their radial energy.

Several recombination processes can be considered. In radiative recombination,

$$\mathrm{p}^- + \mathrm{e}^+ \rightarrow \overline{\mathrm{H}} + h\nu. \tag{1}$$

a photon carries off the extra energy which must be removed to form a bound state. The cross section and rate are small, because the time required to radiate a photon is typically longer than the duration of a collision between an antiproton and a positron. At low temperatures, the cross section σ goes inversely as the relative velocity v squared [21]. The recombination rate per antiproton, $\Gamma = n_e \sigma v$, is therefore inversely proportional to the square root of the temperature of the plasma and proportional to the positron density n_e,

$$\Gamma = 3 \times 10^{-11} \sqrt{\frac{4.2}{T}}\, n_e\ \mathrm{s}^{-1}. \tag{2}$$

Under the conditions discussed earlier ($T = 4.2$ K, $n_e = 10^7/\mathrm{cm}^3$ and $N_p = 10^4$), the antihydrogen production rate is $N_p \Gamma = 3/\mathrm{sec}$.

Radiative recombination can be stimulated by an intense laser,

$$\mathrm{p}^- + \mathrm{e}^+ + h\nu \rightarrow \overline{\mathrm{H}} + h\nu', \tag{3}$$

perhaps to principal quantum level $n = 3$ with a diode laser or to $n = 10$ with a CO_2 laser. The production rate is increased from Γ to $(1 + G)\Gamma$ where

$$G \approx 2 \times 10^{-5} n^5 I\ \mathrm{cm}^2/\mathrm{Watt}, \tag{4}$$

at 4.2 K. This rate is limited by photoionization at high n and by achievable laser intensities at $n \leqslant 8$. Large laser intensities I could be achieved by focussing a relatively weak laser into a small recombination volume. Gains G of up to 100 could be achieved in an ion trap, comparable to gains expected with merged beams of positrons and antiprotons in a storage ring [5].

The cross section for recombination is several orders of magnitude larger if an electron or positron carries off the extra energy. One possibility is colliding positronium with antiprotons in an ion trap [6].

$$\mathrm{p}^- + \mathrm{Ps} \to \overline{\mathrm{H}} + \mathrm{e}^- . \tag{5}$$

However, positronium is neutral and short-lived so that it cannot be confined in the same volume as the antiprotons. Moreover, the coldest available positronium beams are relatively hot (≈ 20 meV) compared to cold plasmas we are considering (< 1 meV). The projected production rate [6] is thus only $N_\mathrm{p}\Gamma = 10^{-3}$/sec for $N_\mathrm{p} = 10^4$ antiprotons.

We call attention to another 3-body recombination

$$\mathrm{p}^- + \mathrm{e}^+ + \mathrm{e}^+ \to \overline{\mathrm{H}} + \mathrm{e}^+ \tag{6}$$

which may well be more efficient for antihydrogen production by many orders of magnitude. Its cross section is also large because the extra positron efficiently carries off the excess energy. This process has the important additional advantage that the reactants are stable charged particles which can be held in a trap, first for cooling to meV and then until recombination occurs. Initial positron capture occurs within a few kT of the ionization limit, producing Rydberg atoms with $n > 100$. The de-excitation of these highly excited states is mainly driven by collisions down to a state where there is insufficient thermal energy to collisionally de-excite. Further de-excitation proceeds via spontaneous emission.

The rate for the equivalent matter recombination, $\mathrm{p}^+ + \mathrm{e}^- + \mathrm{e}^- \to \mathrm{H} + \mathrm{e}^-$, has been calculated in various ways [22] most recently giving [23]

$$\Gamma = 6 \times 10^{-12} \left(\frac{4.2}{T} \right)^{9/2} n_\mathrm{e}^2 \ \mathrm{s}^{-1} . \tag{7}$$

To understand the dependence on temperature and density, we note that the relevant length scale in this reaction is the Thomson radius ($R = 2e^2/3kT$), at which distance the Coulomb interaction between two elementary charges is equal to the thermal energy $3kT/2$. Therefore

$$\Gamma \sim \frac{\left(n_\mathrm{e} R^2 v \tau\right)^2}{\tau} \sim n_\mathrm{e}^2 T^{-9/2} , \tag{8}$$

where v is an average positron velocity (which scales as $T^{1/2}$) and $\tau \approx R/v$ is the duration of the collision. The numerator is the probability for having an interaction of a positron and an antiproton, squared because two positrons are involved. For the temperature and densities we have been assuming, the antihydrogen production rate $N_p\Gamma = 6 \times 10^6$/sec is larger than that for radiative recombination by 6 orders of magnitude! However, the rate decreases so rapidly with temperature that it is not important at the temperatures of 300 degrees or higher which can be achieved within merged beams [4].

The high instantaneous production rate in eq. (7) is very encouraging. However, the applicability of the calculations to 4.2 K is only now being checked in detail [24], the earlier focus being upon temperatures above 100 K, where there is some experimental information [25]. Moreover, the complicated cascade process must rely on spontaneous emission when the energy level spacing becomes too large for collisional de-excitation. For example, de-excitation to $n < 40$ must proceed via spontaneous emission for $n_e = 10^7/\text{cm}^3$. Lifetimes are still long (> 100 μs) at this high n so there is the possibility of the neutral antihydrogen drifting out of the plasma before ground state antihydrogen is formed. One solution may be to stimulate a transition from a Rydberg level to a low-lying state, opening a favorable path for rapid de-excitation. At higher densities there are sufficient numbers of positrons in the high velocity tail of the Maxwell-Boltzmann distribution to collisionally de-excite to lower n levels where the radiative lifetimes are shorter.

We hope that this contribution will also stimulate studies of the effect of external fields upon the recombination processes, since fields have not yet been included in the calculations. For example, a 6 Tesla magnetic field was used to capture antiprotons [1]. Such a field is a strong constraint upon the initial trajectories of the charged antiprotons and positrons. It will also strongly perturb the hydrogen energy levels [26]. In fact, above $n = 26$ the diamagnetic energy shift is comparable to the splitting between energy levels of different principal quantum numbers and n is no longer a good quantum number. It is not immediately clear that a strong or reduced magnetic field will slow the recombination rate since the density of bound states remains large.

An electric field (of order volts to kilovolts per cm) keeps the trapped particles from escaping along the uniform magnetic field axis in a Penning trap. A field of only 7 volts/cm is sufficient to field ionize and thus prevent collisional recombination to hydrogen states with $n > 100$ if no magnetic field is present. The charged plasma rearranges itself until the axial electric field vanishes within the plasma. However, a radial electric field remains within the charged plasma because a magnetic field provides the radial confinement [27]. Before antihydrogen is formed, charged particles travel around magnetic field lines in magnetron orbits for which this radial electric field is exactly canceled by the motional electric field. These radial fields thus only become important as the neutral antihydrogen drifts off a magnetron orbit. When the collision rate is low, this may limit the active recombination region to the center of the plasma, where the electric fields are smaller. On the other hand, a strong magnetic field perpendicular to the electric field can substantially inhibit field ionization [26,28]. If much higher densities can be achieved, the higher collision rate could make these problems less severe. Even so, the atoms formed must be in a low enough energy level by the time they pass through the plasma surface so that field ionization is unimportant.

For a first experiment, the loss of trapped particles to antihydrogen formation can be monitored, with the characteristic n_e^2 dependence of the rate signifying the 3-body process. At the same time, the pions and gamma rays from the annihilation of antihydrogen hitting the walls of the apparatus could be detected. Alternatively, Rydberg atoms formed could be allowed to drift through mesh electrodes and be analyzed by field ionization. Initial experiments could be done with cold protons and electrons to make hydrogen.

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