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ANTIHYDROGEN BY POSITRONIUM-ANTIPROTON COLLISIONS

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A method for producing antihydrogen, $\overline{H}$, by positronium-antiproton collisions is described. Included are the calculated capture cross sections, and short descriptions of the electrostatic slow positron beam, positronium-formation, and the antiproton ion trap to be used for antihydrogen production. With present available technology, collimated monoenergetic $\overline{H}$ beams with an energy of a few keV and an intensity in the order of one per second can be produced by this method. Possible enhancements of this rate are discussed.

1. Introduction

An earlier version of this article is to be published as part of the proceedings of the Workshop on the Physics of Low-Energy Stored and Trapped Particles [1]. This version has been submitted to these proceedings so that all articles on $\overline{H}$-production methods are contained in one volume. The major changes are that the introduction has been abridged, a discussion of $\overline{H}$ production at low energies is included, and other sections have been updated. Otherwise, as before, the following article describes one of the more promising reactions to produce $\overline{H}$ by a simple, technically realisable process–collisions between positronium, Ps, and antiprotons, $\bar{p}$. The three-particle reaction,

$$\bar{p} + Ps \rightarrow \overline{H} + e^-, \tag{1}$$

which involves the release of the electron, e^-, from Ps, conserves both energy and momentum and, as discussed in section 4, has a large cross section such that useful fluxes of $\overline{H}$ can be achieved. One first couples a positron, e^+, to an electron to form positronium at the wall of an $\bar{p}$-ion trap. As orthopositronium, the Ps travels far enough (≈ 1 cm) in the trap to interact with the antiproton to produce $\overline{H}$.

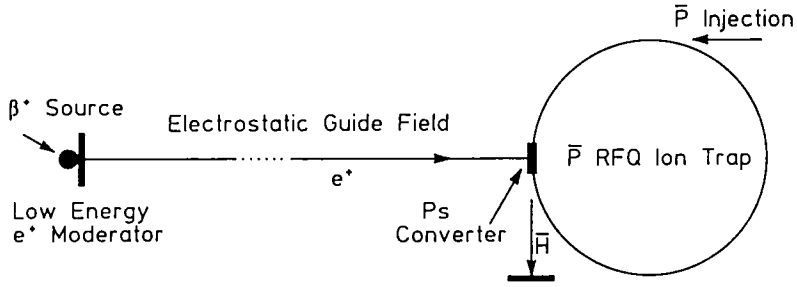

Fig. 1. Schematic arrangement for production of antihydrogen. The β^+ particles from a radioactive source (^{22}Na) are moderated; the slow e^+ are electrostatically focussed onto the Ps converter at the walls of a $\bar{p}$ ion trap (here shown as an RFQ race-track design), from which a collimated $\overline{H}$ beam emerges.

For the realization of antihydrogen via the Ps-$\bar{p}$ process, a cooperation has been formed between DfI (Det fysiske Institut, Aarhus University), LANL (Los Alamos National Laboratories), and UCL (University College London). These institutes will develop and construct a high-intensity, low-energy e^+ beam facility and an RFQ race-track ion trap [2] which can contain a circulating, high-intensity $\bar{p}$ beam. The trap will be equipped with a positronium-formation target and will emit an $\overline{H}$ beam in a possible energy range from zero to 20 keV. A diagram illustrating the operating principles of the system is given in fig. 1. However, before producing $\overline{H}$, our strategy is to optimize the production of hydrogen in the charge-conjugate of reaction (1), namely $p + Ps \rightarrow H + e^+$.

Below we describe details of the low-energy positron-beam line for Ps formation (section 2), the $\bar{p}$(p) ion trap(s) (section 3), the $\overline{H}$-production cross sections and expected counting rates (section 4), and the proposed hydrogen test experiments (section 5).

2. The positron beam and the positronium gas target

A. THE ELECTROSTATIC SLOW e^+ BEAM

Positron moderation and radioactive sources for e^+ beams have been discussed by A.P. Mills [3] and Griffin [4] in these proceedings. Briefly, low-energy e^+ are produced by injecting them at high energy into a moderating material where, following thermalization, a fraction of them diffuse to the surface and may be emitted into the vacuum with a maximum kinetic energy equal to $-w_+$, where w_+, the e^+ work function, is of the order of -1 eV [3]. Alternatively, at the surface, e^+ may be trapped in their image potential or escape by forming Ps if the sum of the e^+ and e^- work functions is less than the Ps binding energy (6.8 eV). Two types of moderator configuration have been employed, namely backscatter-

ing, in which the slow e^+ are extracted from the entering surface, and transmission, in which they are emitted from the opposite surface. The highest efficiency of conversion from fast to slow e^+ obtained for metal moderators is $\epsilon = 3 \times 10^{-3}$ [5] for W(110) used in the backscattering mode, with a ^{58}Co β^+ source, whilst a 5000 Å W(100) foil yielded $\epsilon = 4 \times 10^{-4}$ when used in transmission mode with ^{22}Na [6]. Mills [3] has achieved $\epsilon = 7 \times 10^{-3}$ with a solid Ne moderator at 5 K.

The maximum intensities of slow e^+ beams are typically 10^7 s^{-1} when the high-energy positrons are obtained from a radioactive source [7] or $\approx 10^9$ s^{-1} when pair production from an e^- LINAC is used [8]. Once produced, the slow e^+ can be accelerated and focussed into secondary moderators, termed remoderators, whereby $\approx 20\%$ can be re-extracted from the reduced diameter and with kinetic energies close to $-w_+$. Thus remoderation can be used to enhance the brightness of the e^+ beam [9,10] by circumventing restrictions imposed by Liouville's theorem.

For our purpose, the requirements are to extract slow e^+ produced over an 8–10 mm diameter from a planar (foil) moderator and eventually focus them into another thin foil (the Ps converter) with an ≈ 1 mm diameter and at an energy of a few keV. To achieve this, a compact electrostatic e^+ beam has been designed, a

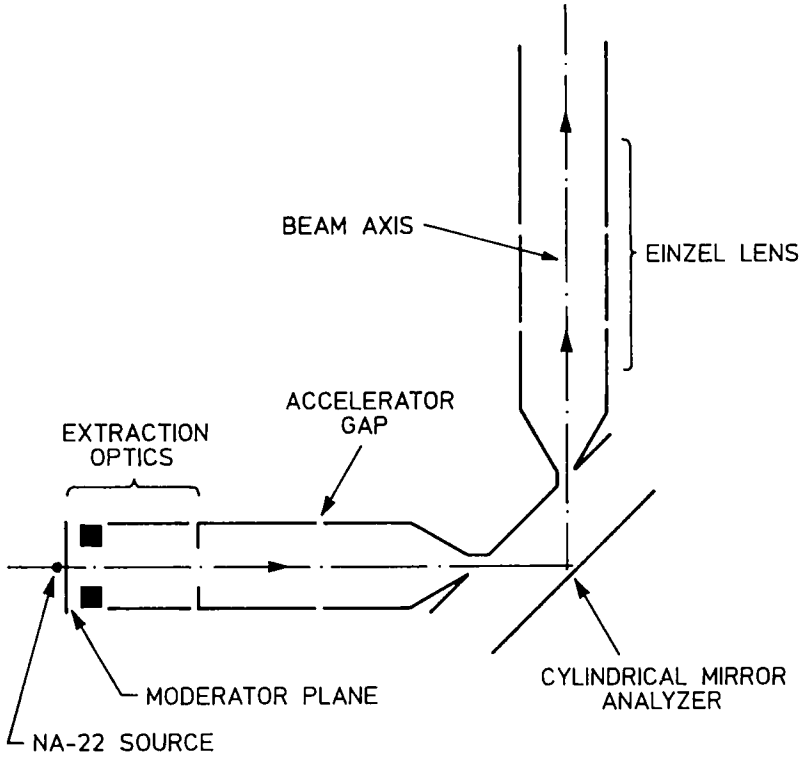

Fig. 2. Schematic electrostatic low-energy positron beam-line.

schematic diagram of which is shown in fig. 2. The beam optics consists of a modified Soa immersion lens [11] e^+ gun, in which the moderator acts as the cathode. The e^+ leave the gun with an energy of 400 eV and are further accelerated to 3 keV before they enter a cylindrical mirror analyzer. Here the beam is deflected through 90° and is thus removed from the primary β^+ and γ-ray background of the radioactive source. The beam is then further transported to the Ps converter foil by means of an einzel lens. Depending on the technical details of the interface with the ion trap and the choice of Ps converter, a final accelerator lens may be inserted after the einzel lens. Trajectory calculations show that, assuming an initial spot size of 10 mm and a transverse energy of 73 meV, an abberated image of better than 2 mm in diameter can be produced.

Due to the lifetime of the $\bar{p}$ in the ion trap and to background pressure problems in the test experiments (see section 5), the apparatus is designed to achieve base pressures in the 10^{-12} torr regime. Initially, a 70 mCi ^{22}Na source will be used in conjunction with a W(100)-foil moderator. Recent investigations with these foils have shown that values of ϵ close to 10^{-3} can be achieved [12,13], using simple annealing and handling techniques.

B. Ps CONVERSION

The slow positrons will be converted into Ps by interaction with a solid surface. Studies [14,15] have shown that Al(111), if used in a backscattering geometry and heated to temperatures of approximately 700 K, converts e^+ of a few hundred eV into Ps with an efficiency close to one. Similar results were obtained at lower temperatures (300 K) after exposing the surface to $\approx$ 1000 L of O_2.

The Ps atoms converted from e^+ incident upon the Al(111) + O_2 surface are emitted with an average kinetic energy close to the temperature of the sample at about 300 K [15], so that the orthopositronium average flight path is 1 cm within its mean vacuum lifetime of 1.42×10^{-7} sec. As for the primary moderator, the Ps converter can, in principle, be employed in either a transmission or backscattering geometry. A transmission configuration for the Ps converter has the advantage over the backscattering type in that it simplifies the interface with the ion trap since the converter can be constructed as an integral part of one of the ground electrodes of the trap. The price to pay is that its efficiency is, at most, only half of what can be achieved in the backscattering mode. If the Ps converter is to be used in the backscattering geometry, the e^+ beam will have to enter the ion trap through a small aperture in one of the electrodes, and their entry energy or injection time must be phase-locked relative to the electrode potentials of the ion trap to ensure that the e^+ are transported and implanted into the Ps converter with approximately equal energies. For the production of antihydrogen, β^+'s from a 0.5 Ci ^{22}Na source moderated with an efficiency of 2×10^{-3} and converted to Ps should yield about $n_{Ps} = 6$ Ps/cm^2 in the ion-trap 0.4 cm dia. target-cell region.

C. IMPROVEMENTS

The above embodiment of the electrostatic facility relies on the present 'state-of-the-art'. However, improvements can be made in the achievable Ps density in the following way: (i) increase the source strength, (ii) increase the efficiency of the primary slow-positron moderator, and (iii) enhance the effective density of the Ps gas target.

The least elegant method to improve the facility is of course to increase the source strength. At Brookhaven, ^{64}Cu is routinely produced with a high specific activity of 166 Ci g^{-1} in a high-flux beam reactor [7]. With a moderator efficiency of about 3×10^{-4}, they have been able to produce e^+-beam intensities of about 3×10^7 s^{-1}. They plan for higher intensities by increasing both the source strength and moderator efficiency. At Risø National Laboratory, ^{64}Cu can be produced to a specific activity of 80 Ci g^{-1}, and at Aarhus, we have the option of using an isotope separator to further enhance the specific activity by several orders of magnitude should this become desirable. In principle, the 10 Ci ^{22}Na source being developed by Griffin [4] can be utilized, although remoderation may be necessary due to the relatively large (1–2 cm) active diameter.

A major improvement in the β^+–e^+ conversion efficiency is expected if a Field-Assisted Moderator (FAM) can be produced. Here, an external electric field is applied to an insulator or a high-purity semiconductor with the aim that a net drift velocity is added onto the random motion (diffusion) of the positrons in the moderator. In this manner, the fraction of the e^+, which reach the emitting surface, can, in principle, be enhanced by one or two orders of magnitude. The use of a FAM was first suggested by Lynn and McKee [16], and a recent theoretical study [17] predicts conversion efficiencies as high as 10–15% for Si operated at 77 K. The problem is now under study at UCL and DfI.

Perhaps the most simple way of enhancing the formation rate of $\overline{H}$ is to maximize the Ps density as seen by the $\bar{p}$ beam (or to minimize the cross section of the ion trap). If the electrodes in the vicinity of the Ps converter are coated with oxygen (or a layer of other nonmetallic atoms), the Ps atoms are expected to survive several encounters with the trap. This expectation is based upon the lifetime measurements of orthopositronium in oxide powders [18,19]. In these experiments, the average free volume per particle ranged from 8×10^{-17}–2×10^{-18} cm^3 with the corresponding orthopositronium lifetimes being 140.8–137 ns. Assuming a thermal velocity for Ps, these results suggest that Ps can survive many encounters with nonmetallic surfaces.

By reducing the space available to the Ps atoms to $0.1 \times 0.1 \times 1$ cm^3, an increase of a factor of ten over the estimated six Ps/cm^2 given earlier can be obtained. A further reduction of the beam diameter can be obtained by the remoderation technique [3]. Although this technique may be accompanied by a loss in beam intensity as high as 90%, a factor of about ten can be gained in the formation rate every time the beam diameter is reduced by an order of magnitude

(down to the size of the $\bar{p}$ beam). Even without mechanical confinement of the Ps atoms, a net gain in the $\overline{H}$-formation rate, $R_{\overline{H}}$, can still be achieved. The Ps density is a strong function of the distance from the impact point of the e^+ beam at the converter. By passing the antiproton beam close (1–2 mm) to this source of Ps, $R_{\overline{H}}$ increases by a factor of 5–10 relative to the beam positioned centrally in the trap. This feature has been included in the RFQ race-track design.

3. Ion traps

In order to design an antihydrogen facility, one must consider not only the production capabilities, storage capacity, but also the dynamic properties of the produced $\overline{H}$ (e.g., their energy range) and their accessibility for later physics experiments. The latter condition in many cases leads to a requirement that the system produces the $\overline{H}$ atoms in a beam. This condition can be realized by confining the $\bar{p}$ in a radiofrequency-quadrupole (RFQ) race-track ion trap, similar to the type originally developed by Church [2]. This device is an extension of the RFQ-mass filter. The transverse confinement of the charged particles is achieved by a radiofrequency field of appropriate amplitude and frequency, whereas the longitudinal confinement is obtained by bending the quadrupole structure into a closed line (race track). Parallel to this design, a standard three-dimensional RFQ trap as well as the standard Penning-trap configuration [20] will be considered since these systems show specific advantages for some applications.

A. AN OUTLINE OF THE RFQ RACE-TRACK TRAP

The detailed theory for the RFQ trap can be found in refs. [21] and [22], and, only a brief description will be given in this paper. Consider an rf potential of the form

$$\Phi = \tfrac{1}{2} U_0 \frac{x^2 - y^2}{r_0^2}, \tag{2}$$

where $2r_0$ is the distance between the electrodes, U_0 is the total applied field comprising a dc component U_{DC} and an rf component with amplitude V_{RF} and frequency Ω. The equation of motion for a particle with mass m and charge e in this potential can be written as

$$d^2r/\,d\xi^2 + (a - 2q\cos 2\xi)r = 0, \quad r = x \text{ or } y, \tag{3}$$

with $a = \pm 4eU_{DC}/m\Omega^2 r_0^2$, $q = \pm 2eV_{RF}/m\Omega^2 r_0^2$, and $\xi = \Omega t/2$, where the signs refer to x and y, respectively. This equation is of the form of the Mathieu differential equations and has stable solutions for certain values of a and q [22,23]. To analyze the behaviour of a particle trapped in this potential in more

detail, we will use the pseudopotential well approach, as introduced by Dehmelt [21]. After averaging over the micromotion of the particle due to the rf drive, a nonzero component remains, which describes a harmonic motion of a charged particle in a parabolic potential well of the form (for $U_{DC} = 0$)

$$D_r(r) = \frac{eV_{RF}^2 r^2}{4mr_0^4\Omega^2}, \tag{4}$$

with the oscillation frequency of the particle being

$$\omega = \left\{ \frac{e^2 V_{RF}^2}{2m^2 r_0^4 \Omega^2} \right\}^{1/2}. \tag{5}$$

Using these results, one can now evaluate the conditions for trapping external particles at a given (longitudinal) energy $E_{\|}$. Because the rf field does not act upon the longitudinal motion, the centripetal force for the motion in the curved section of radius R must be supplied by the radial confinement due to the pseudopotential, e.g., at $r = r_0/2$. This leads to the condition

$$mv^2/R < \frac{e^2 V_{RF}^2}{4mr_0^3\Omega^2}, \tag{6}$$

v being the particle velocity, and, using the definition of q given earlier, to the condition

$$V_{RF} > \frac{16E_{\|} r_0}{eqR}. \tag{7}$$

With $R = 8$ cm and $r_0 = 4$ mm for the dimensions of the trap, the following operational parameters are obtained

$V_{RF} > 6.7$ kV at $\Omega \approx 2\pi \times 82$ MHz for $E_{\|} = 2.5$ keV.

Figures 3(a) and 3(b) show a schematic view of a race-track trap with these parameters.

B. STORAGE CAPACITY AND LOADING OF THE RACE-TRACK TRAP

The maximum density of particles achievable in the race-track trap can be roughly estimated by comparing the space-charge potential of a closed cylinder to the confining pseudopotential. This yields [21]

$$n_{max} = \frac{4\epsilon_0 D_r(r = r_0)}{er_0^2}. \tag{8}$$

where ϵ_0 is the vacuum permittivity. Using the parameters given in the two previous sections, we obtain a maximum density of $n_{max} = 2 \times 10^9$ cm^{-3}. Utilizing only the portion of the trapping volume with a diameter of 4 mm, this gives a maximum total number of stored particles of $N_{max} \approx 10^{10}$. Church [2] was able to

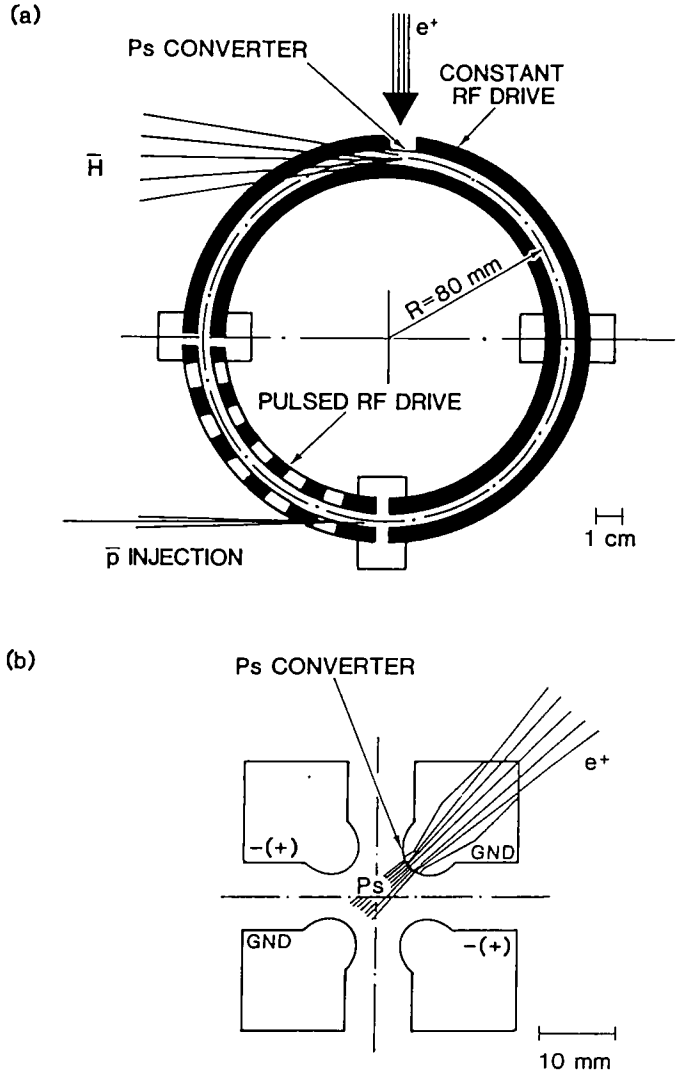

Fig. 3. (a) Schematic layout of the RFQ race-track trap. Shown are the pulsed section for particle injection and the Ps converter. (b) Cross-section view of the RFQ structure. In the upper right-hand quadrant, the Ps converter is shown.

confine 10^5 ions as a plasma in a volume of 3 cm^3 for 8 sec. However, it was never attempted to circulate ions in his trap. The calculated maximum number for his trap was 2×10^9 particles (or a density of 6×10^8 cm^{-3}). The total number of ions was limited by the production mechanism, and higher numbers of stored particles as well as circulation of these ions should be achievable by externally loading the trap. Note that at the keV energy of the antiprotons stored in the race-track trap, the time constant for annihilation on H_2 molecules in the

residual gas is estimated to be sufficiently long so as not to effect the antihydrogen-production rate given later.

At present, the most realistic source of large numbers of antiprotons is the LEAR (Low-Energy Antiproton Ring) facility, located at CERN, Switzerland, which will store a beam of about 5×10^{10} $\bar{p}$ at average momenta 0.1–1.7 GeV/c [24]. This momentum corresponds to an energy substantially greater than the design energy for our $\bar{p}$ trap of 2.5 keV; thus $\bar{p}$'s must be extracted from LEAR, decelerated, and cooled.

The antiprotons stored in LEAR can be extracted in a single pulse and cooled via two possible pathways for injection into the RFQ ion trap:

(a) Perhaps the simplest extraction device can be based on energy-degrader foils such as the beryllium-foil window [25] used to demonstrate the first trapping of antiprotons. The average $\bar{p}$ energy was reduced through collisions in this material to $\leqslant 3$ keV. Recent calculations [26] indicate that up to 20% of an antiproton pulse may be decelerated to $E < 20$ keV by this method and captured into a multi-ring Penning trap. Even higher efficiencies ($\approx 50\%$) can be achieved by extending the energy range of particles being trapped up to 50 keV.

(b) Deceleration and cooling of the antiproton beam can also be accomplished with the RFQ (radiofrequency quadrupole) extraction and cooling system disclosed by Billen et al. [27] for the antiproton-gravity experiment [28]. In this system, the $\bar{p}$ beam energy is degraded to 20 keV through an RFQ decelerating system, including a double harmonic debuncher and a standard RFQ accelerator operating in a reversed mode and an electrostatic drift section at the entrance to the first (Penning) trap, a multi-ring ion trap. Depending upon design parameters and extraction from LEAR, this pathway can yield up to 6×10^8 $\bar{p}$'s in the Penning trap [20], although at greater cost than the foils and at a later date (≈ 1990).

Presently it is planned to use the PS 200 catching-trap structure [20] as a buffer between LEAR and the RFQ race-track trap. Once the $\bar{p}$'s are captured in the PS 200 Penning trap, they will be cooled to an average energy of 1 eV and, due to the harmonic shape of the potential in the z direction, compressed into a spherical volume of about 2–3 mm diameter. After the cooling process is finished, this cloud can be ejected from the catching trap by lowering the downstream half of the potential. Since the center of the catching trap will be floated at a potential of 1–2 keV, the particles will emerge as a short bunch with a small relative energy spread.

Some additional energy spread will be introduced by pulsing the potential, but computer simulations show that this is still less than 10 eV. Using 2 keV and 10 eV for the longitudinal energy and the energy spread, respectively, it is found that the cloud spreads in the axial direction by approximately 1 cm after a 2 m transport. The transverse growth can be controlled by appropriate beam optics which focusses the antiproton bunch onto the entrance gap of the RFQ race-track trap.

The RFQ race track (see fig. 3) consists of 2 sections: A CW section which represents more than three-fourths of the ring structure and a shorter pulsed section. At the time of injection, the rf supply to the pulsed section is turned off, thus allowing the particles to enter the structure. The focussing fields of the CW section will guide the bunch around the first three-fourths turn of the track. By the time the particles reach the pulsed section, the rf drive for this section will have to be turned on, thus closing the trap and completing the capture process. If we assume a 2 cm length for the antiproton bunch and allow an extra 2 cm on either side of the bunch for timing uncertainties (the flight times are in the order of 20 ns/cm), the bunch will travel for 33 cm (670 ns), during which time the rf on the pulsed section will have to be energized. This time is much longer than the period of one rf oscillation (82 MHz = 12 ns), and the pulsed section will be well matched in amplitude and phase to the CW section by the time the first antiprotons arrive at this point. To obtain the 10^8 particles used for the calculation of possible count rates, a transfer efficiency from PS 200 to our system of $\geqslant 50\%$ will be necessary. This should not present a major difficulty.

C. PROPERTIES OF THE FORMED ANTIHYDROGEN BEAM

Upon the formation of an antihydrogen atom, the confining electrical forces will cease to act on the antiproton. Because of the large disparity in masses, the momentum of the positronium atom can be neglected, and the neutral $\overline{\mathrm{H}}$ atom will continue along the trajectory of the antiproton. This enables us to estimate the transverse emittance of the 'beam' emerging from the trap. Initially, the particles injected into the trap will have very little transverse energy. Coupling between the transverse and the longitudinal degrees of freedom is expected only to be caused by imperfections in the potential well setting up resonances. If necessary, the transverse motion can be cooled by coupling to an external circuit. The possible long time constant for this process inherent to the specific design of our trap could be reduced by using the method of active feedback cooling [29]. In this case, the transverse energy $E_\perp$ would be determined by rf heating due to the drive field. It is generally assumed that the limit set by this process is one tenth of the well-depth, but it has been pointed out recently [30] that this effect could be even less severe. Using the conservative ratio of 0.1 for $E_\perp / D_r(r = r_0)$, we obtain, for the anticipated parameters at $E_\parallel = 2.5$ keV, a value of the angular spread of 0.05 radians, which represents a reasonably well collimated 'beam' of antimatter.

4. Antihydrogen-production rate

A. CROSS SECTIONS

Assuming Ps and $\overline{\mathrm{H}}$ are in their ground states, the cross sections $\sigma_{\overline{\mathrm{H}}}$ for reaction (1) have been derived [31] from the knowledge of the cross section of the

inverse process. By CPT invariance,

$$\sigma_{\overline{H}} = k^2 \sigma_{Ps}/\kappa^2, \tag{9}$$

where k and κ are the wave numbers of the positron and Ps, respectively, and σ_{Ps}

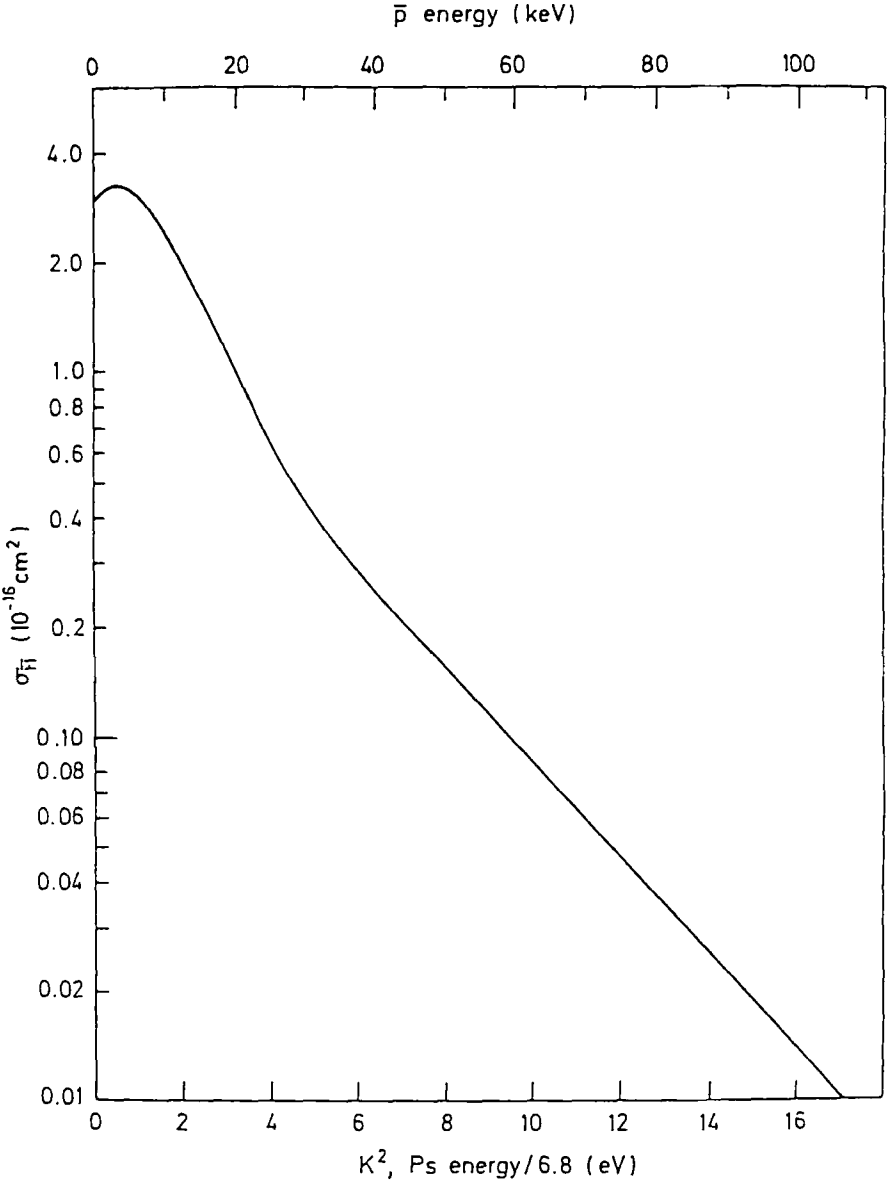

Fig. 4. The ground-state cross section for the formation of antihydrogen in antiproton-positronium collisions at various impact energies (from ref. [31]). The top abscissa gives the $\bar{p}$ energy for the case of a stationary Ps and the bottom refers to the wave number of the Ps in a frame of reference in which the $\bar{p}$ is at rest.

Table 1
Parameters relevant to $\sigma_{\overline{H}}$ at low $\bar{p}$ velocities (see text, section 4.A.)

$\sqrt{\kappa}$ $(a_0)^{-1/2}$	R_{11}	R_{12}	R_{22}	$\sigma_{\overline{H}}$ (πa_0^2)	$\sigma_{\overline{H}}\kappa$	$E_{\bar{p}}$ (eV)
0.05	−0.0551	−0.0064	0.0244	25.8	0.0645	0.078
0.1	−0.0551	−0.0126	0.0964	6.33	0.0633	1.25
0.2	−0.0555	−0.0225	0.3174	1.14	0.0456	20

is the cross section for Ps formation in positron-hydrogen collisions. For the ground-state case, k and κ are related to each other by energy conservation as follows:

$$k^2 - 1 = 0.5(\kappa^2 - 1). \tag{10}$$

When σ_{Ps} is rescaled in the manner described above, the contribution to $\sigma_{\overline{H}}$ from the formation of ground-state $\overline{H}$ is obtained, and the results are given in fig. 4. This cross section has a broad maximum of approximately 3.2×10^{-16} cm^2 at a $\bar{p}$ energy of 2.5 keV.

It is important to examine the behaviour of $\sigma_{\overline{H}}$ at low $\bar{p}$ impact velocities since $\overline{H}$ atoms thus prepared can be trapped more readily for precision spectroscopy and energy-storage applications. In this energy region, it is necessary only to include the s-wave contribution, and following Humberston and co-workers [31,32], $\sigma_{\overline{H}}$ can be written

$$\sigma_{\overline{H}} = (4/\kappa^2)\left|\left(\frac{R}{1 - iR}\right)_{12}\right|^2 = 4R_{12}^2/\kappa^2\left\{\left(1 - R_{11}R_{22} + R_{12}^2\right)^2 + \left(R_{11} + R_{22}\right)^2\right\} \tag{11}$$

in units of πa_0^2, where the R's are coefficients of the 2×2 R matrix given in table 1 [33].

As can be seen from table 1, and as expected from the behaviour of σ_{Ps}, $\sigma_{\overline{H}}\kappa$ asymptotically approaches a constant value for $\bar{p}$ energies $E_{\bar{p}} \leqslant 1$ eV ($v_{\bar{p}} \leqslant 4 \times 10^3$ ms^{-1}). This result implies that the low-energy $\overline{H}$-production rate will be finite and constant since here

$$\sigma_{\overline{H}} v_{\bar{p}} = 8.76 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}.$$

Expected $\overline{H}$-production rates at these low energies are discussed in section 4.B.

Calculations of the total $\overline{H}$-formation cross section using classical and semi-classical methods [34] have obtained values of $\sigma_{\overline{H}}$ which are considerably larger than the ground-state results. Values for the formation of $\overline{H}$ in excited states are given by Ermolaev [35] in these proceedings and are reproduced in fig. 5. These are in good accord with Born approximation results [36] and indicate that there is

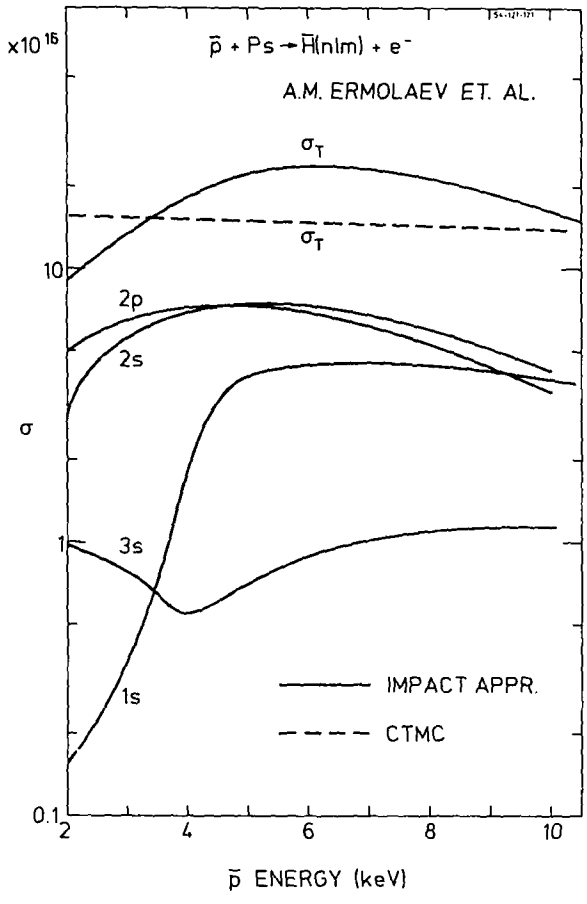

Fig. 5. The cross sections for formation of excited antihydrogen from antiproton-positronium collisions (from Ermolaev [35] in these proceedings).

a large cross section to low-lying excited $\bar{H}$ states, which may prove convenient for a number of later experiments.

B. COUNTING RATES

The production rate of antihydrogen atoms $R_{\bar{H}}$ can be written as

$$R_{\bar{H}} = \sigma_{\bar{H}} n_{Ps} I_{\bar{p}}, \tag{12}$$

where n_{Ps} is the number of Ps/cm^2 and $I_{\bar{p}}$ is the number of $\bar{p}$ traversing the interaction region per second. The $\bar{H}$ will be formed within a $\bar{p}$ RFQ race-track ion trap (see section 3), where the Ps emerge from an Al crystal converter after the impingement of a slow positron beam (see section 2).

For our geometry, it is estimated that in a 4-mm diameter $\bar{p}$ beam, there are six Ps/cm^2 scattering units from a 0.5 Ci ^{22}Na source–W(100) moderator–Al-con-

Table 2
$\bar{H}$-production parameters

Source strength (Ci)	Moderator & efficiency	$\bar{H}$ rate/sec
0.5	W 2×10^{-3}	1
0.5	Ne 7×10^{-3}	3.5
2 *	Ne 7×10^{-3}	14

* ^{22}Na equivalent as ^{64}Cu or LINAC e^+ beam or remoderated 10 Ci ^{22}Na.

verter system. Table 2 lists the expected $\bar{H}$-production rates for various ^{22}Na-source strengths and moderator efficiencies, using eq. (12) with $\sigma_{\bar{H}} = 10^{-15}$ cm^2 (the total cross section), and 10^8 stored $\bar{p}$'s at $E_{\bar{p}} = 2.5$ keV ($I_{\bar{p}} = 1.4\times10^{14}$ $\bar{p}$/sec). Note that although moderation efficiencies as high as 7×10^{-3} have recently been achieved for Ne moderators at low temperatures [3], in our first system, a 0.5 Ci ^{22}Na source and W moderator will be utilized for technical simplicity. If one uses the low-energy $\bar{p}$, asymptotic value $\sigma_{\bar{H}}\upsilon_{\bar{p}} = 8.76\times10^{-10}$ cm^3 s^{-1} deduced in section 4.A, the $\bar{H}$-production rate yielded for $E_{\bar{p}} \leqslant 1$ eV is constant and 10^{-2} times lower than those listed in table 2. Enhancements of this rate are feasible if a different, smaller trap geometry is used.

5. The hydrogen-test experiment

As a first step towards the production of antihydrogen, we plan to measure the cross section for electron capture in collisions between protons and positronium. As mentioned earlier, this reaction has a cross section which is believed to be identical to that for the charge-conjugate process, reaction (1). The purpose of this test experiment is twofold. First, it will provide valuable information about the performance and construction of the Ps target, and, second, it will give experimental cross-section values which are important also for the $\bar{p}$-Ps experiment.

The experiment is planned as a crossed-beam experiment where an $\approx$ 4–10 keV proton beam crosses the thermal Ps 'beam' emerging from the Al(111) + O_2 converter foil. With a 1-mA proton beam from a radio-frequency ion source and present-day Ps-production technology, an estimated rate is $\approx$ 50 H/sec. To avoid background problems, we plan to register the liberated positron rather than the fast hydrogen atoms. The Ps target thickness will also be estimated by the reaction,

$$e^- + Ps \rightarrow e^+ + 2e^-, \tag{13}$$

for which cross sections calculated using the first Born approximation have recently been obtained [37].

6. Conclusion

In this article, a relatively simple, practical method to produce an antihydrogen beam for experimental research has been described. The three-body recombination reaction $Ps + \bar{p} \rightarrow \overline{H} + e^-$ will be utilized. The reaction has a high cross section over a range of $\bar{p}$ energies from 0 to 20 keV. This opens a wide range of applications since the outcoming $\overline{H}$ would have the same range of energies [1]. In its first embodiment with presently available technology, at the cross-section maximum ($E_{\bar{p}} = 2.5$ keV), counting rates of 1 $\overline{H}$/sec should be achievable, with later enhancements of more than a factor of ten being possible. At low energies ($E_{\bar{p}} \leqslant 1$ eV), a constant rate 10^{-2} times these values would be obtained using the same technique.

Finally, use of the positronium-antiproton method means that the properties of our system can be demonstrated and optimized by the charge-conjugate reaction, i.e., through production of hydrogen (see section 5). This is our first experimental goal.

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References

[1] B.I. Deutch, F.M. Jacobsen, L.H. Andersen, P. Hvelplund, H. Knudsen, M.H. Holzscheiter, M. Charlton and G. Laricchia, *Proc. Workshop on the Physics of low Energy Stored and Trapped Particles*, Stockholm (1987). Physica Scripta T22 (1988) 248.
[2] D.A. Church, J. Appl. Phys. 40 (1969) 3127.
[3] A.P. Mills, these proceedings, p. 107.
[4] H.C. Griffin, these proceedings, p. 147.
[5] A. Vehanen, K.G. Lynn, P.J. Schultz and M. Eldrup, Appl. Phys. A32 (1983) 163.
[6] K.G. Lynn, B. Nielsen and J.H. Quateman, Appl. Phys. Lett. 47 (1985) 239.
[7] K.G. Lynn, M. Weber, L.O. Roellig, A.P. Mills and A.R. Moodenbaugh (1988) *Proc. of Workshop on Atomic Physics with Positrons,* eds. J.W. Humbertus and E.A.G. Armoir (Plenum Press, New York, 1987).
[8] R.H. Howell, M.J. Fluss, I.J. Rosenberg and P. Meyer, Nucl. Instr. Methods B 10 (1985) 373.
[9] A.P. Mills, Appl. Phys. 23 (1980) 189.
[10] W.E. Frieze, D.W. Gidley and K.G. Lynn, Phys. Rev. B 31 (1985) 5628.
[11] K.F. Canter, T. Horsky, W.S. Lane and A.P. Mills, *Positron (Electron) Gas Scattering*, eds. W.E. Kaupilla, T.S. Stein and J.M. Wadehra (World Scientific, Singapore, 1986) 202.

[12] N. Zafar, J. Chevallier, F.M. Jacobsen, M. Charlton and G. Laricchia, to be published.
[13] E. Gramsch, J. Throwe and K.G. Lynn, Appl. Phys. Lett. 51 (1987) 1862.
[14] K.G. Lynn and H. Lutz, Phys. Rev. B 22 (1980) 4143.
[15] A.P. Mills and L. Pfeiffer, Phys. Rev. B 32 (1985) 53.
[16] K.G. Lynn and B.T.A. McKee, Appl. Phys. 19 (1979) 247.
[17] C.D. Beling, R.I. Simpson, M. Charlton, F.M. Jacobsen, T.C. Griffith, P. Moriarty and S. Fung, Appl. Phys. A42 (1987) 111.
[18] R. Paulin and G. Ambrosino, J. de Physique (Paris) 29 (1968) 263.
[19] W. Brandt and R. Paulin, Phys. Rev. Lett. 21 (1968) 193.
[20] M.H. Holzscheiter, in: *Low-Energy Antimatter*, ed. D.B. Cline (World Scientific Publications, Singapore, 1986) 120.
[21] H.G. Dehmelt, Adv. At. Mol. Phys. 3 (1967) 53.
[22] J.F.J. Todd, G. Lawson and R.F. Bonner, in: *Quadrupole Mass Spectroscopy*, ed. P.H. Dawson (Elsevier, Amsterdam, 1976).
[23] E.T. Whittaker and G.N. Watson, *A Course of Modern Analysis* (Cambridge University Press, 1950) 404.
[24] P. Lefevré, D. Möhl and D.J. Simon, *Proc. 1st Workshop on Antimatter Physics at Low Energies*, Fermilab, 1986 (FNAL, Batavia, IL, 1986) 69.
[25] G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoekler, T.A. Trainor, H. Kalinowsky, J. Haas and W. Kells, Phys. Rev. Lett. 57 (1986) 2504.
[26] D. Holtkamp, private communication.
[27] J.H. Billen, R.K. Crandell, T.P. Wangler, and M. Weiss, Proc. 3rd LEAR Workshop, eds. U. Gastaldi, R. Klapisch, J.M. Richard and J. Tran Tan Van. Tignes (Editions Frontières, France, 1985) 107.
[28] CERN proposals (PS-94) and (PS-200). Also see T. Goldman, R.J. Hughes and M.M. Nieto, *Proc. 1st Workshop on Antimatter Physics at Low Energies*, Fermilab, 1986 (FNAL, Batavia, IL (1986)) p. 185;
M.V. Hynes, as ref. [1] 195.
[29] N. Beverini, V. Lagomarsino, G. Manuzio, F. Scuri, G. Testera and G. Torelli, Ibid 238.
[30] R. Blatt, private communication.
[31] J.W. Humberston, M. Charlton, F.M. Jacobsen and B.I. Deutch, J. Phys. B: At. Mol. Phys. 20 (1987) L25.
[32] J.W. Humberston, Can. J. Phys. 60 (1982) 591.
[33] J.W. Humberston, private communication.
[34] A.M. Ermolaev, B.H. Brandsen and C.R. Mandel, Phys. Lett. A25 (1987) 44.
[35] A.M. Ermolaev, these proceedings, p. 375.
[36] J.W. Darewych, J. Phys. B: At. Mol. Phys. 20 (1987) 5917.
[37] G. Peach as ref. [7] 423.