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PROGRESS TOWARDS ANTIHYDROGEN PRODUCTION BY THE REACTION OF COLD ANTIPROTONS WITH POSITRONIUM ATOMS

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ABSTRACT

An experiment aimed at producing antihydrogen atoms by the reaction of cold antiprotons stored in a Penning trap with injected ground state positronium atoms is described. The apparatus developed in an attempt to observe the charge conjugate reaction using proton projectiles is discussed. Technically feasible upgrades to this apparatus are identified which may allow, in conjunction with the PS200 trap, antihydrogen production at LEAR.

1. Introduction

The production of the simplest atom of antimatter, antihydrogen ($\bar{H}$), and the prospect of detailed studies of its properties, has recently been the subject of an extended review[1]. Several methods[2-5] have been proposed as possible formation mechanisms. The purpose of this article is to present the experimental progress which has been made for one of these methods, namely the capture of a positron (e^+) from positronium (Ps) atoms by cold antiprotons ($\bar{p}$)[2,6].

This 3-body reaction can be summarised by

$$\bar{p} + Ps(n_{Ps}) \rightarrow \bar{H}(n_{\bar{H}}) + e^- \qquad (1a)$$

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* deceased

which has a cross section $\sigma_{\bar{H}}$ and where n_{Ps} and $n_{\bar{H}}$ are the Ps and $\bar{H}$ principal quantum numbers. From charge conjugation $\sigma_{\bar{H}}$ is equal to σ_H the cross section for the process

$$p + Ps(n_{Ps}) \rightarrow H(n_H) + e^+ \tag{1b}$$

and in section 2 an experiment is described which is an attempt to observe the latter reaction. As detailed in section 3, a number of experimental techniques developed for this purpose can be applied to the observation of $\bar{H}$ formation by reaction 1(a).

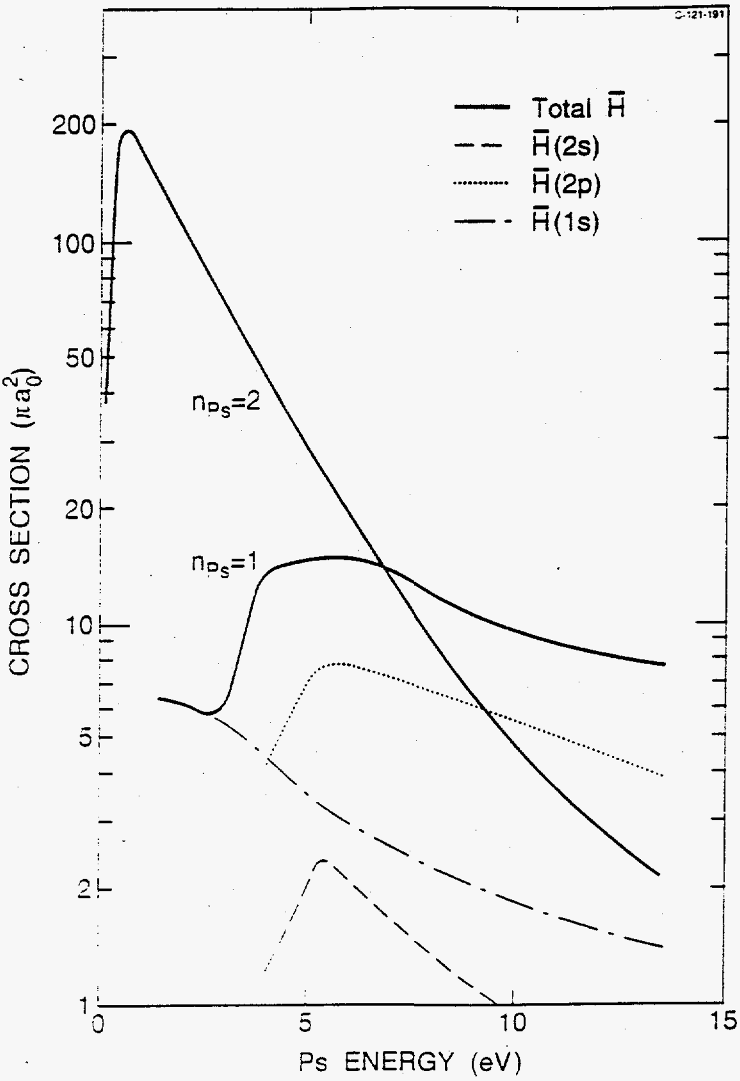

Figure 1. Cross sections for antihydrogen formation in $\bar{p}$-Ps collisions[8]

It was pointed out by Humberston et al[7] that the cross section σ_H was related to that for the time-reversed process, namely Ps formation in positron-atomic hydrogen collisions. This process has been extensively studied, mainly theoretically, as an important 3-body Coulomb problem involving charge transfer. A recent example of this type of work[8] is shown in figure 1 which illustrates how these calculations can be used to generate state-selective cross sections for the p($\bar{p}$)-Ps channel. The data are given in terms of the Ps kinetic energy, since the antiprotons are assumed to be at rest. This is the situation pertaining to trapped antiprotons, though the conditions of the charge conjugate experiment described in section 2 are closer to that in which the protons are moving and the Ps is stationary.

A number of years ago[9] it was realised that $\sigma_{\bar{H}}$ could be enhanced by using excited states of Ps as an antiproton target by the (semi-classical scaling) factor of the fourth power of n_{Ps}. Figure 1 illustrates this effect and shows the results of the first quantum mechanical calculation for $n_{Ps} \rangle 1$. The cross section for $n_{Ps}= 2$ is 3-4 times greater at its maximum than that for $n_{Ps}= 1$, and is also shifted to lower Ps energies. This is also expected since it is known that capture conditions are most favoured when the semi-classical speed of the captured e^+ (in the Ps) matches that of the projectile.

Experimentally, the controlled production of excited state Ps for $\bar{H}$ production remains a long term goal. In the remainder of this article we will concentrate on the use of ground state Ps, whose production and implementation in vacuum using low energy e^- beams has been extensively documented[10-12], both in an effort to observe the charge conjugate reaction 1(b), and in terms of the prospects for $\bar{H}$ formation via rection 1(a) at CERN.

2. The Charge Conjugate Experiment

In this experiment a pulsed low energy positron beam is made to impinge upon a thin heated silver target which acts as a high vacuum source of Ps atoms. An intense proton beam crosses the Ps target and the occurence of reaction 1(b) is signalled by the detection of the fragment e^- in time relation to the initial e^+ pulse. For convenience we will divide the discussion into two basic parts, namely the pulsed e^+ beam and the proton-Ps scattering chamber. An estimate of the expected reaction rate will also be given. The proton beam, which consists of a current of 100-200μA, is extracted from a standard r.f. source and accelerated to an energy of around 9keV before being focussed into a 2-3mm diameter as it crosses the Ps gas.

A schematic illustration of the pulsed e^+ beam is shown in figure 2. Note that the beamline vacuum chamber can be floated and that the source end, deflector and buncher are also electrically isolated from one another. The voltage values shown in figure 2 refer to the voltage above ground at which each section of the apparatus is floated.

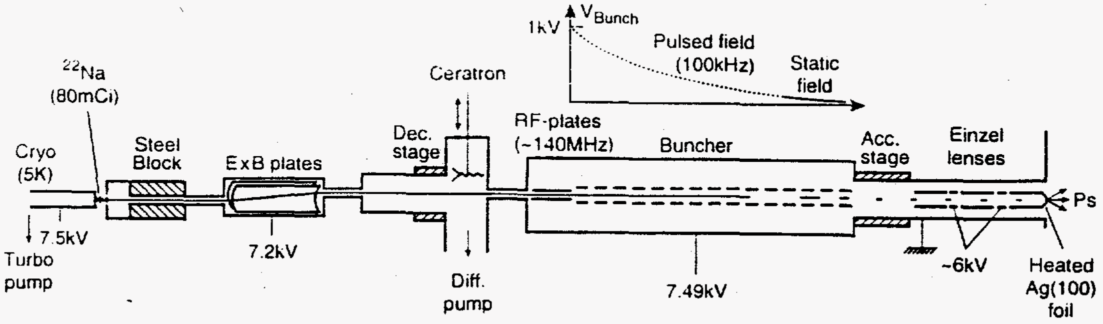

Figure 2. The pulsed low energy e^+ beam (see text)

The slow e^- are produced using a solid rare gas moderator (frozen onto the cold finger of a closed cycle helium fridge) bombarded by β^+ particles from a 3GBq (80mCi) ^{22}Na radioactive source. Previous experience[13,14] with such moderators had identified solidified Kr as being efficient and robust and, as such, is used here. The slow e^+ are accelerated to 300eV in the confining (axial) magnetic field of around 10^{-2}T and deflected 25mm using a pair of curved **ExB** plates[15]. This, together with appropriate shielding, removes the remainder of the beamline from direct line-of-sight with the radioactive source. The e^+ are then decellerated to around 10eV to pass into the buncher. At this point the d.c. beam has an intensity of around $5\times10^6 e^+ s^{-1}$.

The bunching region is one metre long and consists of 50 equispaced cylindrical elements each 19mm long, all individually hard-wired to external voltage feedthroughs. As shown in figure 2, the latter part of the buncher is wired with a d.c. voltage which reflects the 10eV e^- so that they pass back towards the buncher entrance. The remainder of the electrodes are capacitively chain-coupled such that a voltage pulse applied suddenly to the input end produces a voltage distribution down the entire buncher which, as shown schematically in figure 2, varies quadratically with distance. As is well known[16,17] the application of such a potential distribution leads to the time-focussed ejection of any e^- in the buncher. For particles initially at rest, the ideal time focus occurs at the end of the device, independent of the amplitude of the applied voltage. In practice though, due to the initial motion of the particles in the buncher, the position of the time focus is located outside the buncher and has to be found empirically. It is not, fortunately, at the voltage used here (1kV) strongly dependent upon position outside the device over a length of around 100mm. The capacitive coupling allows the buncher to be run at the relatively high frequency of 100kHz at a pulse amplitude of 1kV, a rise time of less than 5ns, a duration of 120ns, followed by a decay with a characteristic time constant of less than 500ns. The e^+, which at present are not accumulated in the buncher (though r.f. plates[16] have been incorporated for this purpose which will be implemented at a later stage - see section 3), arrive at random times with respect to the switching of the buncher. At present, the bunching efficiency is around 10%, close to that expected from a simple consideration of the frequency of operation and the time spent by the low energy e^+ in the pulsed section of the device. The time spread of the bunch has been measured to be below 5ns. The switching signal of the buncher is used as a timing trigger to identify the e^+ liberated in reaction 1(b).

The e^+ leave the buncher and are accelerated through 7.5kV whilst the 10^{-2}T field is terminated using soft iron shielding (not shown in figure 2). Electrostatic einzel lenses then transport the e^+ onto the Ps production target (or convertor) - a 0.2μm thick Ag(100) film located, as shown in figure 3, in the proton-Ps scattering chamber and heated to around 800K using the halogen lamp.

Investigations using slow e^+ beams have shown that thin Ag(100) films can be used for the production of Ps both in backscattering and transmission geometries[18,19]. In the latter the Ps is produced on the opposite side to the e^+ implantation, thus allowing physical and electrical separation of the e^+ impinging at keV energies, and the extraction of the low energy e^+ liberated in reaction 1(b). Ps is produced in transmission by 10-20% of the incident e^+ which, by virtue of their spread of starting positions in the buncher, have energies in the 7.5-8.5keV range. The foil can be used continuously for many hundreds of hours.

The proton beam is brought to a focus around 2mm in front of the Ag(100) foil. Alignment is effected by an aperture mounted on one of the stack of two lens elements which can be moved vertically onto the e^+ beam axis. This lens element also contains a W mesh arrangement which the e^+ beam can strike and which can be used as a remoderator to test the extraction optics and detection of the e^+ fragment. The other element contains the Ag(100) foil Ps convertor.

The fragment e^+ are accelerated by applying 600V across the 20mm gap between the Ag(100) foil and a copper mesh joined to the first lens element of the extraction optics. Note that the stray magnetic fields in this chamber can be cancelled by a system of two orthogonal pairs of Helmholtz coils (not shown in figure 3). Positrons liberated in reaction 1(b) should, by virtue of their position of creation in the acceleration gap, have a mean energy of around 550eV. These are then deflected through two 90^0 bends (only one is shown in figure 3) using fields produced by sector magnets, which have to be finely tuned to allow the passage of the e^+ to the channel electron multiplier array (CEMA) detector. Heavy ions are hardly deflected by the small fields necessary to bend the e^+ and are thus undetected. The purpose of the double bend is to reduce, as far as practicable, the background signal of the CEMA due to stray light produced both by the

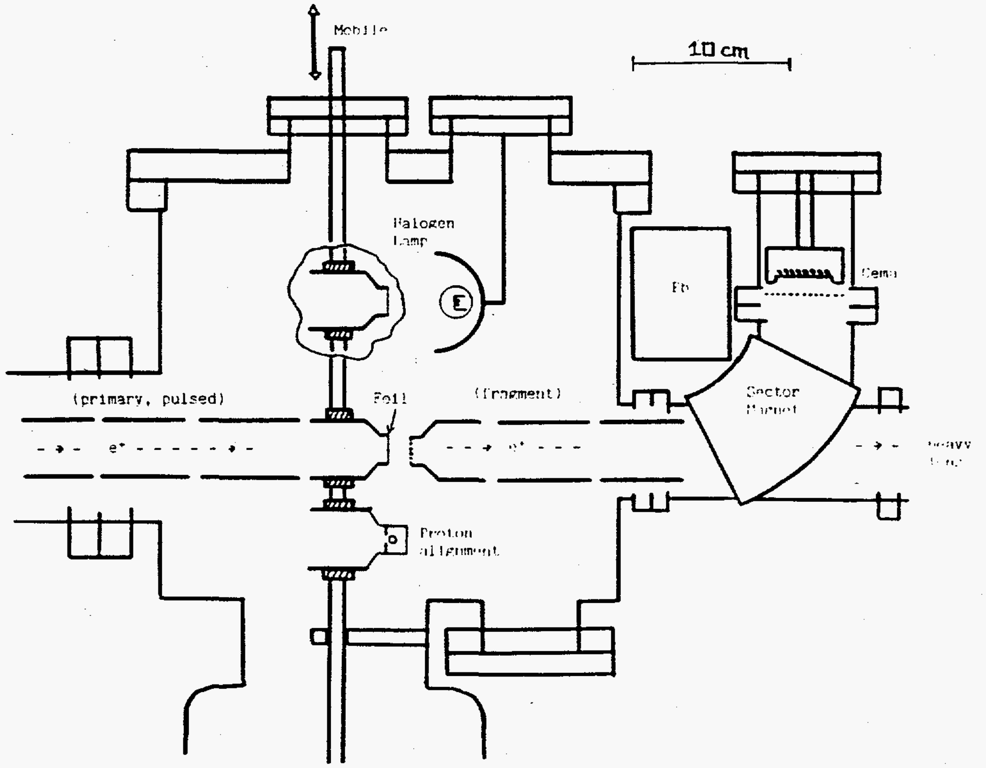

Figure 3. The proton-Ps scattering chamber. Note that the fragment e^+ are now bent twice by sector magnets to reach the CEMA.

passing proton beam and the energetic ions which pass along the first length of the extraction optics. The CEMA is also position sensitive in the vertical direction, which gives some discrimination since the e^+ kinetic energy is dispersed along this axis. If necessary this detector can also be placed in coincidence with a NaI(Tl) detector, located close by, to unambiguously identify a e^+ signal, before being placed in delayed coincidence with the trigger of the primary e^+ beam buncher. Given the sub-5ns resolution of the bunched beam and the time difference between the arrival of the e^+ liberated in reaction 1(b) (which includes the Ps time-of-flight to the interaction region) and any e^+ which exit the foil at low energies (which therefore must have kinetic energies in excess of 600eV), it is expected that signal e^+ can be distinguished from others which will appear at earlier times. It should also be noted that the work of Ermolaev et al[20] has shown, as expected at proton kinetic energies below 10keV, that reaction 1(b) will dominate e^+ liberation by Ps dissociation (target ionisation).

The current status of the apparatus is as follows. The bunched e^+ beam and the proton beam are constructed, the proton-Ps scattering chamber is complete and the e^+

extraction optics has been tested independently using secondary beams of low energy e^+ and e^- generated by the input e^+ beam. Effort is now going in to testing all of these parts assembled together. By using the calculated cross section (6×10^{-16}cm^2), beam strengths ($5 \times 10^6 e^+ s^{-1}$ and 150μA proton current), the production efficiency of Ps in transmission from the heated Ag foil (10%), the o-Ps lifetime (142ns) and realistic detection and bunching efficiencies the estimated event rate will be around $10^{-2} s^{-1}$, which should be distinguishable above background.

3. Prospects for CERN

The production of $\overline{H}$ at CERN using reaction 1(a) will, most likely, require interfacing a low energy e^+ beam with a trap containing cold antiprotons. The pulsed e^+ beam described in section 2 could, with modifications, be suitable for this purpose. The major change needed is to accumulate e^+ in the buncher such that the repetition rate of the device can be lowered whilst improving the efficiency. This can be achieved using the technique developed by Mills[16] in which a combination of electrostatic and magnetic mirrors, and the application of r.f. radiation to excite the cyclotron motion of the particles between the two mirrors, served to trap the particles. The r.f. plates (see figure 2) have already been installed for this purpose. Our goal using this, perhaps in conjunction with an associated device, is to accumulate e^+ for around one second. Positron storage times of 40 seconds have recently been demonstrated using a trap based upon gas moderation[21].

The magnetic field used to confine the slow e^+ in the present arrangement is around 10^{-2}T, compared to the 4T currently used in the PS200 trap. Injection of e^+ from the beam to the trap in the presence of such a large field gradient may present problems due to mirroring, though these can probably be solved by accelerating the e^+ as they are injected into the high field.

Recently, as summarised elsewhere in these proceedings, the PS200 trap has caught over 10^5 antiprotons, with an efficiency of 0.25% of those ejected at 5.9MeV in a single LEAR spill, and held them with a lifetime of around 12 minutes. In this sequence of runs the antiprotons were not cooled by electrons which had been pre-loaded into the central harmonic region of the large Penning trap. This was probably due to the lack of overlap between the antiproton and electron clouds. Further work is planned to investigate whether the lifetime was limited by annihilation on the residual gas, or reduced as a result of instabilities due to the antiproton motion in the large catching trap, and to implement electron cooling. The goal here would be to increase the antiproton lifetime to at least one day such that expected annihilations on the trap walls resulting from $\overline{H}$ production would be similar to the background level caused by antiproton annihilation on the rest gas. Such investigations will also help in deciding the conditions under which e^+ injection into the trap must take place.

For use at CERN the pulsed e^+ beam should operate at a frequency of around 1Hz (or less) such that the full d.c. intensity (currently $5x10^6s^{-1}$) is contained in the ejected bunch. This can be used to form a Ps cloud where after approximately 1.5μs the ground state $m=\pm1$ components (the only long-lived Ps in the large magnetic field) have all but decayed. After this time antihydrogen, depending upon the exact trap configuration and its temperature (including that due to the recoil in reaction 1(a)), could be detected by its annihilation on a trap wall in a time window say 10μs wide. The detection could be done using scintillators, or some other suitable substitute. The detection duty factor of 10^{-5} implied above should be useful in reducing background from cosmic rays and other sources to a low level. With around 10^7 antiprotons assumed stored in the trap the lifetime has to be around 1 day (corresponding to an annihilation rate of $80s^{-1}$) in order to reduce the number of recorded annihilations to around 80 per day. (Of course longer antiproton lifetimes and e^+ accumulation times would serve to reduce the background further - the values quoted above show the minimum requirements, and are realistic goals based upon the experience of others[21,22]).

The figures given above, together with the cross section shown in figure 1, can be used to derive a rate for reaction 1(a). This has been done recently by Deutch[23] for the case of a cloud of N antiprotons with a radius r located at a distance d from the source of Ps (assumed to be a point) produced with an efficiency ε from a positron beam with an intensity I. They found the reaction rate to be $R=[4N\sigma_{\bar{H}}I\varepsilon(\tan^{-1}(r/d))^2]/\pi^3r^2$, which by inserting $N=10^7$, $\sigma_{\bar{H}}=6x10^{-16}cm^2$, $I=5x10^6s^{-1}$, $\varepsilon=0.2$, $r=2mm$ and $d=8mm$ resulted in a rate of approximately 100 per day. This estimate has fixed the minimum antiproton lifetime and e^+ accumulation time as discussed above.

4. Conclusion

We have described a programme whose eventual aim is to create antihydrogen by the reaction of trapped antiprotons with Ps atoms. Progress towards the observation of the charge conjugate reaction 1(b) has been summarised. The pulsed e^+ beam to be used in that experiment could be used at CERN, in conjunction with the PS200 antiproton trap, to form antihydrogen. Some of the main developments necessary to achieve this have been discussed.

We believe that the creation of low energy antihydrogen in vacuum by this, or any other means, is an important goal in atomic and fundamental physics. The LEAR facility is the only place worldwide where such a programme can be carried out.

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