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TITLE: TRAPPING OF ANTIPROTONS - A FIRST STEP ON THE WAY TO
ANTIHYDROGEN

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SUBMITTED TO: Workshop on Traps for Antimatter and Radioactive Nuclei
VanCouver, February 25-27, 1993

CONF-930274--3
CST/

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Trapping of Antiprotons - A First Step On The Way to Antihydrogen

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Abstract

A first step towards producing and effectively utilizing antihydrogen atoms consists of trapping antiprotons. The immediate next step must then be to control, i.e. trap the produced antihydrogen. The current state of the art in trapping antiprotons and positrons is reviewed, and the challenges in trapping the resulting neutral particles are discussed.

I. INTRODUCTION

The simplest system which studied by atomic physicist, the only one where theory can even attempt to find exact solutions, and the one which has subsequently been studied with great success, both theoretically and experimentally, is the hydrogen atom. Naturally, it is a tantalizing thought to be eventually able to study with the same precision its mirror image, the antihydrogen atom, either to solidify, or to expand our understanding of fundamental symmetries.

By stating this goal, I restrict myself to the discussion of possibilities to obtain antihydrogen in an experimental environment suitable for precision measurements comparable to those achieved on the hydrogen system. Adding the novel restriction, that antihydrogen will always be an extremely rare object, one immediately realizes, that it is a sensible approach to cool and trap the antihydrogen atoms.

Much of the work which will be described in these notes has been performed by other groups. In the true sense of a workshop, for which this article was written, I only take the liberty to summarize, challenge, and comment on a variety of issues. It is my hope, that this will initiate a deeper discussion amongst groups interested in the future of this field. For a more detailed technical view, the reader is advised to consult the references given throughout this paper.

2. ANTIHYDROGEN PRODUCTION

A variety of schemes for producing antihydrogen ^{have} ~~has~~ been proposed, and discussed in some detail [1-14], with the first mentioning of the possible production of antihydrogen in traps by Dehmelt and co-workers [15]. Below I list a selection of these processes (with appropriate references), of which only a few will be discussed here in detail. The first line shows the basic production mechanism of combining a positron and an antiproton to form a neutral atom. A photon in the final state carries away excess energy and momentum. All following schemes (except the last one) are based on attempts to increase the effectiveness of recombining antiprotons and positrons by either laser stimulation of the radiative recombination process [3], or by using a three-body process [4-12]. The last line describes a method which is currently pursued at Fermi Lab [13] and at CERN [14], where an antiproton picks up a positron from Bremsstrahlung pairs generated when the antiproton passes through a gas target. The resulting antihydrogen atom will have an extraordinary high energy, which will render it useless for high precision measurements, but this method may yield the first observation of antihydrogen atoms produced in the laboratory.

For all practical purposes, only processes (3), (6), and (7) deserve close attention by the trap community. In the first case, both constituents forming antihydrogen need to be trapped, while in the last two cases only antiprotons need be controlled before the recombination process, while the positron is delivered in form of beam of positronium. Both methods have distinct advantages and disadvantages and, dependent on the final application, either one might be the better choice.

1. Antihydrogen production using trapped plasmas.

This method has originally been proposed, and discussed extensively, by G. Gabrielse's group [5]. In a "nested trap" scheme, forming two Penning traps, the oppositely charged constituents for antihydrogen production are held in separate clouds and cooled to 4 K, or possibly below [16]. At a definite time, the two clouds are merged by lowering the electrostatic barrier between them, and antihydrogen is formed. The rate constant for this process is strongly temperature dependent :

$$(10) \quad \Gamma = 6 \times 10^{-12} (4.2/T)^{9/2} n_e^2 \text{ s}^{-1},$$

and therefore benefits vastly from cooling the particles. Because of the mass difference between positrons and antiprotons, with positrons at 4.2 K, the antiprotons could have energies as high as 1 eV, before the recombination rate is significantly affected. As Gabrielse points out [5], this could be used to form eV energy beams of antihydrogen atoms leaving the trap volume. The beam quality would strongly depend on how well the axial energy of the antiprotons could be decoupled from the radial energy.

While the rate can be extremely large (with $10^7/\text{cm}^3$ positron density at 4.2 K one obtains $\Gamma = 6 \times 10^6/\text{s}$), a number of problems for practical applications have been identified by the original authors of this proposal: The antihydrogen atoms are being formed in highly excited Rydberg states ($n > 100$), and need to be quickly de-excited, before electrostatic field gradients from the Penning trap will ionize these states, or before spectroscopic studies could be attempted. A mixture of collisional and spontaneous de-excitation may be used, provided the antihydrogen does not drift outside the positron plasma on the same time scale. Additionally, magnetic field effects both on the recombination process and on the survival of the antihydrogen Rydberg atoms need to be studied in more detail before a final assessment of advantages and disadvantages of this method for a specific application can be made.

Alternative methods to store both positrons and antiprotons simultaneously have been proposed. A Paul trap, which is insensitive to the sign of the charge could be used for simultaneous confinement in the same volume [15]. Also, the potential use of a combined Paul and Penning trap for simultaneous confinement of positrons and antiprotons for the purpose of antihydrogen formation has been pointed out [17]. On

the other hand, keeping the positrons and antiprotons apart until they are cooled to extremely low energy, and then producing antihydrogen with high rate constants as a well defined burst may have advantages for a number of applications.

2. Antihydrogen production by Positronium-Antiproton Collisions

Alternatively one may enhance the radiative antihydrogen formation rate by several orders of magnitude by coupling the recombination process to a third particle for energy and momentum conservation via collisions between positronium atoms and antiprotons [10]. This process can be interpreted as Auger capture of the positron to the antiproton and cross sections have been estimated by Humberston et al. [9], using charge conjugation and time reversal to link the cross section for positronium formation in collisions between positrons and hydrogen to the antihydrogen formation cross sections. Early calculations assumed both $\bar{H}$ and Ps to be in the ground state. Results of these calculations are given in figure 1, showing a broad maximum for the production cross section of $3.2 \times 10^{-16} \text{ cm}^2$ at a $\bar{p}$ energy of 2.5 KeV. Calculations of the total $\bar{H}$ -formation cross section using classical and semi classical methods [18] have obtained values of $\sigma_{\bar{H}}$ which are considerably larger than the ground-state results. Values for the formation of $\bar{H}$ in excited states are given by Ermolaev et al. [19] and indicate that there is a large cross section to low-lying excited $\bar{H}^*$ states (Figure 2).

M. Charlton [12] has discussed the formation of excited $\bar{H}^*$ atoms via collisions between antiprotons and excited positronium. The cross section follows a classical n_{Ps}^4 scaling, where n_{Ps} denotes the principal quantum number of the positronium atom, leading to large enhancements in the reaction rate. This process can also be utilized to preferentially populate specific low level excited states for spectroscopic purposes. An additional feature of the excited state process is the low recoil energy of the resulting $\bar{H}$ atoms. By energy and momentum conservation the recoil temperature arising from the binding energy difference ΔE between $\bar{H}$ and Ps^* is given as

$$(11) \quad T_{\bar{H}^*} = 2\Delta E m / 3kM = 28.6 \left(\frac{2}{n_{\bar{H}}^2} - \frac{1}{n_{Ps}^2} \right) K,$$

where m and M are the mass, and $n_{\bar{H}}$ and n_{Ps} are the principal quantum numbers of the positron and antiproton, respectively. Waiving the requirement of negligible kinetic

energy of the positronium would add additional terms of order mT_{Ps}^*/M . Resonant charge transfer is taking place for $n_{\bar{H}} = \sqrt{2} n_{Ps}$, when the initial and final states are degenerate in energy. A range of $\bar{H}^*$ states close to resonance will be preferentially populated, allowing a certain degree of selection of the final $\bar{H}^*$ excited state.

Figure 3 shows a plot of $T_{\bar{H}^*}$ vs. $n_{\bar{H}}$ for fixed values of n_{Ps} ranging from 1 - 10 and in addition the asymptotic value at $n_{Ps} = \infty$. This figure can be used to determine the states of the product $\bar{H}$ atom with recoil energies below the well depth of a specific neutral atom trap. As an example, for $n_{Ps} = 4$, the states with $n_{\bar{H}} = 3, 4$, and 5 will be populated and exhibit recoil energies below 4 K, for $n_{Ps} = 10$, $n_{\bar{H}}$ values of 7 - 14 yield $T_{\bar{H}^*} < 1$ K with $n_{\bar{H}} = 15$ just being energetically forbidden.

A final note on rates: much discussion has been put forward about the difference in rate constants for $\bar{H}$ production using either one of the processes discussed here. In essence, this discussion may be viewed as non relevant if the product $\bar{H}$ is to be trapped. A limited number of antiprotons being available to work with, there is no fundamental difference between a rate of $10^6/\text{sec}$, converting all antiprotons to $\bar{H}$ in a single second, or a rate of 1000/sec (or even 100/sec), requiring a production cycle of 16 minutes (or 3 hours), which still is much shorter than the storage time of antiprotons in traps of several months. The antihydrogen atoms produced are intrinsically stable and long term storage must be a goal for experimental reasons anyway.

II. EXPERIMENTAL CONSIDERATIONS

In this section, I wish to comment on a few technological developments necessary to achieve the ultimate goal of producing and trapping antihydrogen atoms. What has been a collection of "wild and crazy ideas" just a few years ago has now reached a level where "serious proposals, based on technical achievements by a number of groups during the last 5 years", can be prepared [20].

1. Production and trapping of low energy positrons

Since the rate constant for recombination of antiprotons and positrons in plasmas (10) is proportional to the square of the positron density, it is important to accumulate significant numbers of positrons and compress them into a small volume. Densities typically considered by the authors of these proposals are $10^7 \text{ e}^+/\text{cm}^3$. A number of schemes are under investigation for achieving these densities in traps. The

very first capture of positrons into a Penning trap dates back to 1980. Dehmelt and co-workers [21] used a radioactive source (0.5 mCi of ^{22}Na) placed off axis outside the end cap of a Penning trap. Positrons emitted with low axial kinetic energy entered the trap and were deflected by the opposite endcap. By the time they returned to the entrance hole they had undergone a small azimuthal drift due to the magnetron motion ($\mathbf{E} \times \mathbf{B}$ drift) and saw a slightly higher potential. This enhanced the time period before the positrons could possibly escape from the trap by a factor ω_z/ω_m (≈ 2000). During this time, enough axial energy could be extracted by coupling the axial motion to an external damping resistor so the positrons could be trapped. The total efficiency of this method was only 3 out of 10^{10} captured positrons (23 e^+/hour), quite sufficient for the experiment at the time, but not acceptable for reaching high densities.

An important first step to improve this situation is the reduction of the energy of positrons emitted from radioactive sources, or produced at linear accelerators, using moderators. Positrons from radioactive sources and from LINAC production targets exhibit a broad continuous spectrum with very high upper energy values. If these positrons are implanted into a solid, most are thermalized 0.1 to 1 mm deep from the surface, and a substantial fraction will thermalize near the surface of the material. These positrons are the ones which can, if sample and surface conditions are suitable, be reemitted from the surface before annihilation. Some materials show a negative work function for positrons, therefore emitting positrons as a low energy ($\approx 1\text{-}2$ eV), mono energetic ($\Delta E \approx 1$ eV) beam, preferably normal to the surface. A wealth of references exists in the literature on this topic, with recent reviews by Schultz and Lynn [22] and M. Charlton and G. Laricchia [23].

The first observation of this phenomenon was by Cherry in 1958 [24] with an efficiency of 10^{-8} , first experimental evidence of efficient (10^{-7} to 10^{-6}) generation of low energy positrons was reported in 1968 by Groce et al. [25]. Since then the efficiency has been improved steadily over several orders of magnitude, with the highest values reported to date being nearly 10^{-2} , using solid neon moderators [26]. Weber et al. used a solid neon moderator and a magnetic guiding system to deliver 5×10^6 e^+/sec to an experiment at Brookhaven [27].

The challenge remains to trap these positrons in a trap, where they can then be allowed to recombine with the antiprotons by either merging the clouds or by allowing the antiprotons to traverse the positron cloud with eV type kinetic energies. C. Surko et al. [28] trapped of the order of 100 positrons for short times using collisions with a buffer gas for cooling. This environment is incompatible with the extreme vacuum

requirements for antiproton storage, and a final UHV stage for this experiment would need to be developed, in which positrons could be accumulated before being transferred to the antiproton trap.

A scheme to stack and accumulate positrons has been proposed by R. Conti et al. [29] using a dynamic two trap system. The first confining potential is increased continuously at a rate sufficiently high, that positrons entering the potential well from a moderator can not reach the moderator again on the first bounce. Once a specified potential is reached (≈ 5 kV), the accumulated positrons are accelerated towards a second moderator and injected in a similar fashion into the final storage volume [8,29]. Due to the now narrow energy spread of the positrons, this remoderation process has a comparable high efficiency. Again, a significant accumulation of antiprotons has not been proven to date.

The last method discussed here has been proposed by Brown et al. [30]. Using the same basic scheme as Dehmelt et al. [21] it relies primarily on the higher intensity of low energy positrons available through above described moderator techniques. The lower energy positrons will also allow a more effective damping by resonantly coupling to the external circuitry than was possible with the relativistic positrons in the original work. Subsequently to the trapping the positron cloud would be compressed by sideband centering of the magnetron motion to achieve the proposed number of 10^6 positrons at a density of 10^8 e⁺/cm³ (using a 20 mCi ²²Na source).

2. Sources of (ground state and excited) positronium

In many materials a finite probability exists that positronium (Ps) will form as a positron leaves the solid surface and travels through the decreasing electron density just outside. Conservation of energy gives a positronium formation potential, which in many cases can be negative, assuring the positronium formation to be one of the main branches for positrons diffusing back to the surface. First efficient positronium formation was observed by Canter et al. [31]. Mills later showed the effect to be 30% to 100% on well characterized surfaces, and also studied the dependence on the incident positron energy [32]. A significant fraction of the Ps is formed in the ortho-positronium state with a vacuum life time of 142 nsec. Since the kinetic energy of the emitted positronium is approximately a few eV (depending on the temperature and the specific positronium formation potential of the surface), these Ps atoms can travel a distance of 10 cm or more, before annihilation occurs. In the presence of a magnetic field this life time is quenched due to admixtures of para-positronium states. Therefor

care must be taken in designing the experiment and placing the positronium converter as close to the trapped cloud of antiprotons as possible. Alternatively, a electro-dynamic trap, i.e. a Paul trap [33] or an RFQ ring trap [10,34], can be used for antiproton confinement, thereby avoiding the presence of any magnetic fields.

Excited positronium with n_{Ps} ranging from 13 to 19 has been produced by Ziock et al. [35], using a two quantum excitation. First the 1S-2P transition was pumped and then 2P - n_{Ps} transitions were excited by a second laser beam. The production of highly excited Ps by recombination of merged e^+ and e^- plasmas has also been observed by Cowan et al. [36]. Still, significant work lies ahead in adapting all these techniques into a single experiment..

3. Trapping and cooling of antiprotons

Antiprotons are produced at very high energies, with the lowest energies at which they are delivered to physics users at this time being 2 - 5 MeV at the Low Energy Antiproton Ring (LEAR) at CERN [37]. To further reduce this energy a number of methods have been proposed and tested: Deceleration by a Radio-Frequency-Quadrupole Accelerator (RFQ) operated in reversed mode [38], slowing down antiprotons in a dilute gas in the 'Anti-Cyclotron' [39], and degrading the antiproton energy by passing the beam through thin foils [40,41]. Matching the RFQ acceptance to the phase space of the LEAR output beam has been identified as a main problem of the first method, and an experiment using an RFQ to decelerate an antiproton beam from 2 MeV to 200 keV [42] has recently been abandoned. Initial tests of the Anti-Cyclotron approach have been performed, with current development continuing at the Paul Scherrer Institute (PSI) in Switzerland using muons [43]. The degrading foil method has been used by two experiments at LEAR with promising results during the last years [44,45], and I wish to discuss this method in some more detail.

When protons or antiprotons pass through matter they loose energy by collisions with the nuclei of the material. If the thickness of the material is increased particles eventually are stopped in the material, and, in the case of antiprotons, annihilate. Using the computer code TRIM91 [46], which is based on energy loss data for protons, one can calculate the expected linear density of material at which a maximum number of particles with low energy is transmitted, and how large the number for a specified energy bin should be. One finds this optimum thickness to be near the point where 50% of the incoming particles are transmitted. Adjustments for

different stopping powers for protons vs. antiprotons (the Barkas Effect [47]) must be made empirically. These calculations predict as much as 5% of the incoming antiprotons being transferred into an energy bin of 0 to 50 keV [45]. At this energy it is possible to electro-magnetically capture the antiprotons into a Penning trap and to further reduce their temperature using electron cooling [44], stochastic cooling [48], or resistive cooling [49].

This method has been successfully used by experiment PS196 [44] with a capture efficiency of 2×10^{-4} per keV well depth. More than 20000 antiprotons have been captured into a small Penning trap and cooled to temperatures below 100 meV, using collisions of the antiprotons with a cold buffer gas of trapped electrons. Observed cooling times were approximately 10 seconds. Energy widths as small as 9 meV have been directly observed by releasing the trapped antiprotons from the trap. After the antiprotons are cooled, the trap well can be lowered to accept a new pulse of antiprotons into the same trap. This method of "stacking" has been demonstrated by the PS196 team and approximately 100,000 cold antiprotons have been captured into the Penning trap utilizing about 10 consecutive pulses from LEAR.

In order to determine the ultimate efficiency that can be achieved for degrading and capturing antiprotons into a Penning trap, the first part of the PS200 experimental set-up was installed at LEAR [45]. This part consists of an open end-cap Penning trap of 50 cm total length and 3.8 cm diameter, situated in a 6 Tesla super conducting magnet with a horizontal, cryogenic bore. The maximum design potential for this structure is 60 kV. At this time a commercial switch is in use, which is capable of switching up to 30 kV with 100 ns rise times. Figure 4 shows the general layout of the experiment and the different detectors used to monitor the incoming beam and to verify the capture of antiprotons.

A particle pulse from LEAR is transported to the front end of the experiment, which contains a parallel plate avalanche counter (PPAC) for beam monitoring. After exiting the LEAR beam line through a 12 micron titanium window, passing through the PPAC chambers, a gas cell for fine tuning of the energy degrading, and reentering the vacuum system through another 12 micron titanium window, the beam energy has been reduced to approximately 3.7 - 4.0 MeV. Due to the transverse scattering in the material the particles have to pass through, a relatively large angular spread is introduced into the beam, which is focused by the fringe magnetic field of the 6 Tesla super conducting magnet. A correct choice of the magnetic field strength for the particular energy of the incoming beam places a focal point at the entrance foil of the

trap. In this 135 micron gold coated aluminum foil the antiprotons will lose energy by collisions with the atoms of the foil material and, assuming proper adjustment of the additional degrader material upstream, an optimum number of low energy particles will exit from the downstream face of the foil. These particles will be reflected by the electrical potential at the far end of the trap and travel back towards the entrance electrode. This electrode is ramped up to potential before the particles can escape, thereby capturing them within the volume of the trap.

The principal design parameter for the trap is the length necessary to capture particles of energies up to 30 (60) keV emerging from this foil during a LEAR pulse of typically 200 ns duration. At a 1 m round trip distance, the time remaining after the last particle has entered the trap before the first particle is reflected back to the entrance is 220 ns (95 ns) for a 30 kV (60 kV) well depth. Our current 30 kV pulser has a 125 ns rise, allowing a total of 95 ns for jitter and uncertainty in the trigger timing.

To detect the capture of low energy antiprotons, they are released from the trap after a predetermined storage time and detect the annihilation of p-bars on the surface of the microchannel plate detector (MCP) by scintillators outside the magnet dewar as well as by direct counts from the MCP. The release is accomplished by lowering the potential of the downstream end-cap of the trap linearly with a time constant large compared to the oscillation period of the particles in the trap. Particles will escape from the trap when their kinetic energy is greater than the potential barrier. This generates a time-of-arrival spectrum which reflects the energy distribution of the particles in the trap prior to the release. Figure 5 shows such an energy spectrum of 30,000 antiprotons released from the trap 500 msec after the pulser had fired to capture the first pulse delivered from LEAR to our experiment.

4. Neutral particle traps

Having discussed the generation and trapping of all necessary components to form antihydrogen the final task, by far not the least, is to combine all this into an environment which allows trapping and studying of the neutral (anti-)atoms. Much of the development work on trapping antihydrogen atoms can be guided by the excellent work by the groups at MIT [50,51,52] and Amsterdam [53], who have developed technology to magnetically confine neutral hydrogen atoms. This work is well documented in the given references and I can concentrate on giving a brief summary and on discussing a few essential differences.

The confining force being the magnetic gradient interaction with the magnetic moment separates the (anti-)hydrogen in the high-field seeking ($H\downarrow$) and the low-field seeking component ($H\uparrow$: ($F=1, m=1$ and $F=1, m=0$)). Even though work with hydrogen has been performed with both states, only the low field seeking states are of use in the case of antihydrogen, where collisions with the walls of the containment vessel are unacceptable. The trap configuration used for the latter case normally consists of an arrangement of coils, designed to produce a magnetic minimum at the center of the trap without having a zero field location, which would introduce spin-depolarizing Majorana transitions. The essentially cylindrical geometry of these traps has been proposed by Pritchard et al. [50] and provides transverse trapping forces by a set of super conducting race track coils which generate a quadrupole field. Axial confinement is achieved through coaxial solenoids at either end of the trapping volume, which provide a barrier against axial leakage and also the non-zero field value in the center. As a specific example, the magnetic field values in the Amsterdam trap [53] are 1.5 Tesla for the quadrupole fields at $r = 6.5$ mm and 1.5 and 1.7 Tesla for the coaxial coils respectively, with the field minimum at the center adjustable between $B = 0$ and $B = 1$ T.

In filling the magnetic traps in the hydrogen work, the "gas" is allowed to fall into the potential well by inelastic collisions with residual gas atoms, a method unacceptable for antihydrogen. A possible alternative would consist of either superimposing the magnetic trap and the Penning trap in a way where the Penning trap is located within the potential well for the confinement of the neutral atoms. Antihydrogen produced in the high-field seeking states would quickly leave the trap volume, while the $H\uparrow$ states would be attracted towards the center. To achieve continuous confinement, the well depth will have to be substantially larger than the kinetic energy at which the antihydrogen is formed, or effective laser cooling needs to be employed, to quickly cool down the antihydrogen atoms after formation. Using 1.5 Tesla for the magnetic well depth, initial confinement would be limited to atoms with $T < 1$ Kelvin. Active laser cooling could increase this value, if the ($H\uparrow$) antihydrogen atoms would be allowed to move in form of a beam in the opposite direction to a cooling laser for a time sufficiently long to absorb the 10 photons necessary (under maximum momentum transfer conditions) to essentially stop the antihydrogen atoms. This could be achieved by placing the recombination location towards one end of the magnetic well so that the magnetic field minimum would be just the required distance away for laser cooling to work optimally.

A number of points of concern to groups working towards Bose Einstein condensation of hydrogen, like loss mechanism through dipole relaxation and other density dependent effects, are clearly not a problem here, since densities of 10^{10} - 10^{12} cm^{-3} are far beyond any reasonable goal based on the availability of antiprotons and positrons, and on the needs of specific experiments suggested. Stability of the antihydrogen cloud against dipole relaxation losses is given by the rate $\Gamma = nG$ (with $G = 1 \times 10^{-15}$ cm^3/sec [54]), which yields a lifetime of 100 days for antihydrogen densities as high as even 10^8 cm^{-3} . Clearly other mechanism will dominate before then.

A more serious concern must be raised with respect to the spin polarisation requirement to initially stabilize the antihydrogen atoms. Only atoms with electron spin $+1/2$ will be low field seeking, and therefore confined by the magnetic configuration. If antihydrogen atoms would be formed only in the ground state, it may be conceivable that either the statistical population of these states is high enough, or that optical pumping from the $1S_{1/2}$ manifold to the $n=2$ states could be used to populate these states. But what if the antihydrogen is formed in low lying excited states, or even in high n Rydberg states. The routes of de-excitation will obviously proceed via all possible magnetic sublevels, many of them not trapable. This could lead to a significant reduction in the efficiency for trapping the produced antihydrogen atoms.

III. CONCLUSIONS

Far from being complete, I attempted to summarize the steps necessary to produce antihydrogen under conditions suitable for high precision spectroscopy or for a measurement of gravitational interactions of antimatter. Significant progress has been made on all fronts, but this must not blind us for the intrinsic difficulties to put all these different, very challenging, state-of-the-art experiments together into one single unit. Also a number of specific issues need to be clarified before the best possible combination from all the different proposals can be constructed. But if it would not be such a formidable challenge to experimental physicists, it would be only half the fun to work on. Over the last few years a number of meetings have demonstrated the rapidly increasing interest in this field, and shown a surprisingly rapid rate of advancement, that there remains no doubt that antihydrogen will eventually become a standard tool of physics.

IV. ACKNOWLEDGMENTS

Much of these comments result from work done in collaboration with groups from the University of Aarhus, Denmark, and the University College in London, U. K., and I would like to thank all members of these groups for helpful conversations during the last years. This work was supported by the Danish Natural Science Research Counsel (SNF), the Carlsberg Foundation, EC (contract SCI-CT91-0964 (TSTS)), and the U. S. Department of Energy under contract W7405 ENG-36.

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FIGURE CAPTIONS

Figure 1: The ground-state cross section for the formation of antihydrogen in antiproton-positronium collisions. The top abscissa gives the antiproton energy for the case of a stationary Ps and the bottom abscissa refers to the wave number of the Ps in the antiproton rest frame. (from ref. [9]).

Figure 2: The cross section for formation of excited state antihydrogen in collisions between antiproton and ground state positronium. (from ref. [19])

Figure 3: Antihydrogen recoil temperature, $T_{\bar{H}^*}$, versus $\bar{H}^*$ principal quantum number, $n_{\bar{H}}$, for various Ps* principal quantum numbers n_{Ps} . (from eq. (11))

Figure 4: Layout of experiment PS200/T to study antiproton capture at LEAR

Figure 5: Energy spectrum of trapped antiprotons immediately after capture. The horizontal axis gives the kinetic energy of the antiprotons with channel 0 = 15 keV and channel 560 = 0 keV.

Figure 2

Figure 3

LEAR CATCHING TRAP SET - UP

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