Letter of Intent
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The Production and Study of Cold Antihydrogen

by the
Antihydrogen TRAP Collaboration (ATRAP)

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1 Introduction and Motivation

When the TRAP Collaboration (PS196) brought its initial proposal to the predecessor of the SPSLC committee, we estimated that we could eventually compare the charge-to-mass ratios of the antiproton and proton to 1 part in 10^9 (1 ppb). Last year, the TRAP Collaboration announced that its initial 1 ppb goal had been achieved [1], thereby improving on previous comparisons of the antiproton and proton by a factor of 45,000. Moreover, an additional improvement by as much as a factor of 10 is expected in 1996. (The history of comparisons of antiproton and proton is shown in Fig. 1.) Now we turn our attention to a greater challenge: comparing hydrogen and antihydrogen to high accuracy. Our original collaboration is now expanding to include groups with needed expertise and similar records of accomplishment. We are confident that we will again be able to develop the techniques that are required and to solve the problems that arise. This Letter of Intent to the SPSLC expresses our determination to produce and study cold antihydrogen.

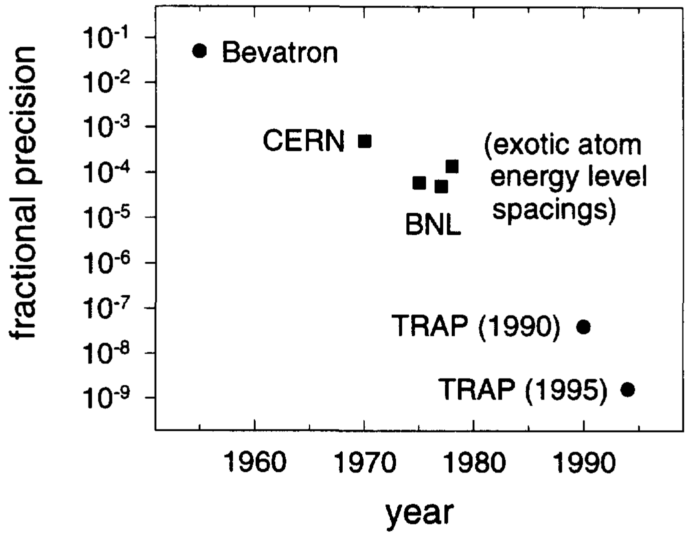

Figure 1: The accuracy at which antiprotons and protons have been compared.

An improved CPT test is one important motivation for experiments which compare antihydrogen and hydrogen. A reasonable requirement on any new CPT test is that it eventually be carried out with an accuracy that exceeds the accuracy of the best tests with baryons and leptons. Right now, the most accurate test of CPT invariance with a baryon system is the 1 ppb comparison of the antiproton and proton mentioned above. The most accurate test of CPT invariance with a lepton system establishes that the magnetic moments of the positron and electron [2] are the same within 2×10^{-12}. These tests of CPT invariance with baryons and leptons are nonetheless still much less accurate than was attained by comparing the mass eigenvalues of the $\bar{K}_0$ and the $\bar{K}_0$ mesons [3]. The delicately balanced nature of the unique kaon system makes it possible to deduce and compare the differences of these mass eigenvalues to an accuracy of 1×10^{-18}, an accuracy much greater than the fractional accuracy required in the measured quantities. (Recent theoretical speculations [4] suggest that quantum gravity could produce a CPT violation which is smaller by only a factor of 10.) The three most accurate tests of CPT invariance are represented in Fig. 2.

The narrow resonance line shown in Fig. 3 (obtained by one group in this collaboration [5]) illustrates the possibility to use laser spectroscopy to greatly improve the accuracy of CPT tests involving baryons and leptons. The observed width of this line is only 1 part in 10^{11} of the frequency being measured. Because this narrow observed width is still much wider than the natural linewidth, we expect that the steady improvements in the accuracy of hydrogen spectroscopy measurements

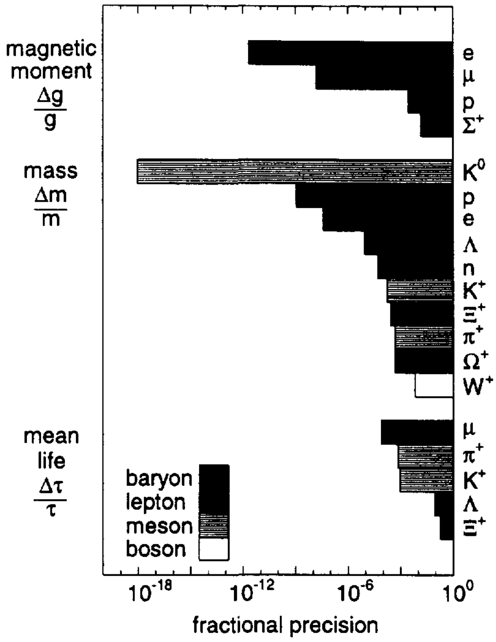

Figure 2: Tests of CPT Invariance. The particle - antiparticle pair is identified on the right. The shading indicates whether the comparison involves leptons, mesons or baryons. The accuracy achieved in the comparison is indicated below. Charge-to-mass ratio comparisons are included in "mass" measurements.

will continue as they have for many years. If such a line were available for antihydrogen as well as hydrogen, the signal-to-noise ratio would be sufficient to allow the frequencies to be compared to at least 1 part in 10^{13}, a large increase in accuracy over the current tests.

A second motivation for experiments which compare cold antihydrogen and hydrogen is the possibility to search for differences in the force of gravity upon matter and matter [6]. Making gravitational measurements with neutral antihydrogen atoms certainly seems much more feasible than using charged antiprotons, for which the much stronger Coulomb force masks the weak gravitational force. Members of the TRAP Collaboration have considered the possibility of gravitational measurements with trapped antihydrogen [7], and routinely time the free fall of cold atoms released from a trap [8]. We are intrigued by the possibility of experimental comparisons of the force of gravity upon antihydrogen and hydrogen, but are not yet ready to make specific estimates of attainable measurement accuracies.

Considerable progress toward the production and study of cold antihydrogen has already been made insofar as the raw materials for cold antihydrogen are now available. The TRAP Collaboration (PS196) developed the techniques whereby antiprotons from LEAR are now routinely slowed in matter, trapped [9], and then electron-cooled to 4 K [10, 11]. The surrounding vacuum is so good that antiprotons have been stored for months at an energy 10^{10} times below the energy of antiprotons in LEAR [11]. One group in our collaboration also developed the techniques to accumulate many 4K positrons in a similarly good vacuum [12]. These trapped antiprotons and positrons are an important step towards the recombination envisioned long ago by members of the TRAP Collaboration [13], who also suggested that cold antihydrogen be stored in a magnetic trap for precise measurements [14]. Such recombination and storage of antihydrogen, and the spectroscopy of small numbers of stored atoms, are the central challenges that remain.

Of course, no cold antihydrogen can be made and studied unless cooled MeV antiprotons are available. The only such antiprotons ever available came from the unique LEAR facility at CERN,

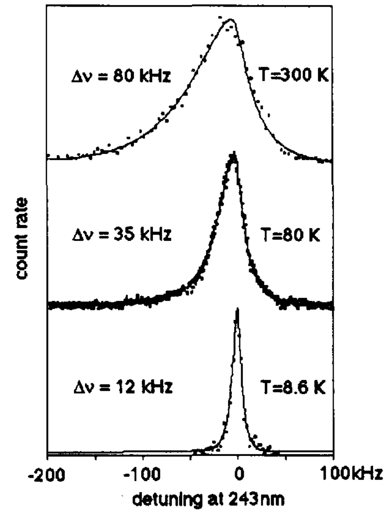

Figure 3: Narrow resonance line of the $1s - 2s$ $(F = 1)$ transition in hydrogen.

which closes at the end of 1996. This Letter is therefore presented in support of the proposed Antiproton Decelerator (AD). The AD is a partial replacement for LEAR, delivering 100 MeV/c pulses that are less intense but available more frequently. This is a workable mode of operation insofar as the TRAP collaboration has demonstrated that successive pulses of such antiprotons can be accumulated within a trap [10, 11] rather than in the CERN's Antiproton Accumulator (AA).

In the remainder of this Letter, we will look more carefully at what has been accomplished and what remains. Most importantly, we will identify the collaboration which has been formed to pursue these antihydrogen experiments. To the TRAP Collaboration we are adding research groups which have been leading the research in hydrogen spectroscopy, experiments with trapped hydrogen (and other atoms), the production of Lyman alpha radiation, laser cooling, and in other areas. The expertise of each group and the contribution that each group expects to make will be specified. The groups signing this Letter are committed to making these difficult experiments work.

The 9 antihydrogen atoms that were recently observed [15] caused considerable excitement, even though their small number and extremely high energy make it impossible to make any accurate measurements. The Antiproton Decelerator (AD) should allow the production and study of cold antihydrogen which can be accurately compared to hydrogen.

2 Expanding the TRAP Collaboration

This Letter of Intent to the SPSLC committee concerns the production and study of low energy antihydrogen. The goal is to produce extremely cold antihydrogen from cold antiprotons and positrons, capture it in a trap via its magnetic moment (as has been done for hydrogen), and then compare it to hydrogen spectroscopically. We are encouraged in this difficult undertaking by the remarkable convergence of experimental advances made in the last several years. Of particular importance to the production and study of cold antihydrogen are the following.

1. The slowing, trapping, cooling and stacking of antiprotons at 4K in extremely high vacuum.
2. The slowing and trapping of large numbers of 4K positrons in high vacuum.
3. Demonstration of the simultaneous trapping of protons and electrons, with clear evidence that these particles interact at low relative velocity.

4. The laser cooling of atoms.
5. The trapping and spectroscopy of cold hydrogen atoms.
6. Higher accuracies being steadily achieved in the spectroscopy of hydrogen.

The TRAP Collaboration is expanding to include leading contributors to the experimental advances listed above. They will join with members of the original TRAP Collaboration, who will coordinate the new generation of antihydrogen experiments, thereby insuring that the new techniques developed to accumulate 4K antiprotons will be optimally utilized in a new apparatus. The expertise of members of the expanded TRAP collaboration are described below, accompanied by a list of responsibilities.

Expertise and Responsibilities

Prof. G. Gabrielse of **Harvard University** has directed the antiproton experiments of the TRAP Collaboration (PS196), and many other experiments with trapped particles. His group designed and built the antiproton trap, and recently accumulated substantial numbers of cold positrons in a similar trap, within the extremely high vacuum required to avoid the annihilation of antihydrogen. They also have demonstrated (with protons and electrons) that antiprotons and positrons could be made to interact at low relative velocity. Dilution refrigerator apparatus now being tested could eventually make it possible to study antihydrogen recombination at temperatures below 0.1K.

1. *Trap for antiproton accumulation, and radiofrequency diagnostics.*
2. *Positron trap which can be loaded from a radioactive source (or another source if this becomes more attractive).*
3. *Nested Penning trap, after demonstrating with protons and electrons that this is the most desirable way to produce cold antihydrogen.*
4. *Coordinate the collaboration.*
5. *Contribute to the operation of the experiment*

Dr. H. Kalinowsky of the **University of Bonn** has been an important collaborator in many aspects of the PS196 experiments, contributing especially to the data acquisition electronics. He has a deep understanding of the CERN capabilities and resources based upon extensive experience with the ASTERIX, Crystal Barrel and PS196, and has also carried out earlier experiments with trapped particles.

1. *Real time imaging annihilation detector and electronics (shared with Öhlert).*
2. *Coordination of the data acquisition system.*
3. *Contribute to the operation of the experiment.*

Prof. W. Jhe of **Seoul National University** has been part of the trap collaboration for several years, contributing to the accurate comparison of the antiproton and proton.

1. *Carry out the trajectory modeling needed to optimize the positioning of antiproton degrader and trap.*
2. *Contribute to the operation of the experiment.*

Prof. T. Hänsch from the **Max Planck Institute for Quantum Optics** of Garching is known for developing many of the techniques for accurate hydrogen spectroscopy. He, his associate Dr. Claus Zimmermann, and his group have achieved a precision in hydrogen spectroscopy sufficient to contemplate the comparison of hydrogen and antihydrogen to 1 part in 10^{15}. They have also demonstrated that a combined Penning-Paul trap can simultaneously store positive ions and electrons.

1. *A combined Penning-Paul trap, after demonstrating with protons and electrons that this is the most desirable way to produce cold antihydrogen.*
2. *Lasers for stimulated radiative recombination and spectroscopy.*
3. *Develop the spectroscopy of small numbers ($n \leq 1000$) of hydrogen atoms.*
4. *Contribute to the operation of the experiment*

Dr. W. Oelert of the **Jülich Laboratory** led the team that first observed 9 antihydrogen atoms, and has participated in JetSet Collaboration at LEAR. The collaboration will profit from his experience with the detection of antihydrogen annihilation.

1. *Real time imaging annihilation detector and electronics (shared with Kalinowsky).*
2. *Contribute to the operation of the experiment*

Prof. J. Walraven of the **University of Amsterdam**, along with his associate Tom Hijmans, has both trapped hydrogen atoms in a neutral particle trap and observed them with a Lyman α source constructed in his group. His group has extensive experience studying spin polarized hydrogen confined at low temperatures.

1. *Magnetic trap for antihydrogen.*
2. *Contribute to the operation of the experiment when the magnetic trap is incorporated into the experiment.*

Dr. W. Phillips of the **National Institute of Standards and Technology** (Gaithersburg), along with his associate Dr. S. Rolston, were the first to substantially slow atoms with a laser, and the first to capture neutral atoms in a trap, similar to what is required for antihydrogen. This group has constructed a coherent source of Lyman α radiation.

1. *Provide lasers for the laser cooling of antihydrogen.*
2. *Contribute to the operation of the experiment when this laser cooling is incorporated into the experiment.*

Dr. D. Wineland of the **National Institute of Standards and Technology** (Boulder) was a coinventer of the laser cooling technique for trapped ions. Among many experiments, his group is now investigating the possibility of using their trapped and laser cooled Be^+ ions to trap and cool extremely large numbers of positrons.

1. *Provide laser technology to cool Be^+ ions, after demonstrating the desirability of using such ions to accumulate positrons more efficiently.*
2. *Contribute to the operation of the experiment if this technique for accumulating positrons is adopted.*

3 The Ingredients for Cold Antihydrogen are Available

3.1 Extremely Cold Antiprotons: Techniques Developed by the TRAP Collaboration

The possibility to produce and study cold antihydrogen arises out of the techniques developed by the TRAP Collaboration (PS196). Antiprotons from LEAR are slowed in matter, trapped in ultrahigh vacuum ($< 5 \times 10^{-17}$ Torr), electron-cooled and accumulated at 4 K, which is an energy that is 10^{10} below the energy of antiprotons from LEAR. These techniques of the TRAP collaboration, of course, are only possible because the unique LEAR facility of CERN delivers a high quality, 100 MeV/c antiproton pulse.

This Letter presupposes that the proposed Antiproton Decelerator (AD) facility will deliver antiprotons in 100 MeV/c pulses, comparable in quality to current pulses from LEAR. The pulses will be less intense, but will be available much more frequently. The antiproton stacking technique should allow the accumulation of antiprotons from successive pulses within the trap (instead of in CERN's Antiproton Accumulator). With a beam quality comparable to that in LEAR, the techniques developed at LEAR can be directly used. Since these techniques are well-known to the committee, and each was announced in Physical Review Letters, we simply list them with references.

1. Slowing antiprotons in matter from 6 MeV to below 3 keV [9]
2. Capturing Antiprotons in a Trap [9]
3. Electron Cooling of Trapped Antiprotons [10]
4. Stacking of Antiprotons [10, 11]
5. Demonstrating a Pressure Below 5×10^{-17} Torr [10, 11]

Up to 2×10^5 antiprotons have been captured by PS196 from a single pulse from LEAR. A comparable number has been cooled to 4K and stacked in a trap. It certainly is possible to initially capture larger numbers of antiprotons in a larger trap, as has been confirmed recently by the PS200 collaboration [16], which has reproduced some of the techniques mentioned above in a larger trap. We are currently working to design the optimum geometry for producing cold antihydrogen. (A large trap can capture more antiprotons, but they are not useful unless they are eventually confined with a high density of positrons in the same small volume.)

3.2 Accumulation of 4K Positrons in High Vacuum

Members of our collaboration recently accumulated many 4 K positrons in the extremely good vacuum required to avoid antiproton and positron annihilations [12]. The hyperbolic Penning trap used to accumulate these positrons is represented in Fig. 4. High energy positrons from a ^{22}Na source passed through the trap (following the magnetic field lines) to strike and enter a single crystal of tungsten. This crystal was suspended by extremely thin wires to allow it to be cleaned and annealed by briefly heating it white hot while its surroundings are at 4 K. Positrons diffuse in the crystal without being trapped at defects, slowing via collisions. Most of the positrons thermalize in the crystal and some diffuse back to the surface of the crystal where they are ejected at low energies by the work function [17].

The cooled positrons, with energy spread less than 1 eV, reenter the trap, again traveling along the (vertical) magnetic field direction. The trap is carefully biased to keep some of the positrons inside for one "magnetron" revolution period (as shown in Fig. 5) during which they oscillate harmonically along the direction of the magnetic field. These positrons would naturally leave the trap after this 10μs revolution, exiting the trap through their entrance hole. During their time in the trap, however, the rapid vertical oscillations induce a current in a resonant tuned circuit attached to the electrodes. The positrons lose the energy that is dissipated in this circuit and

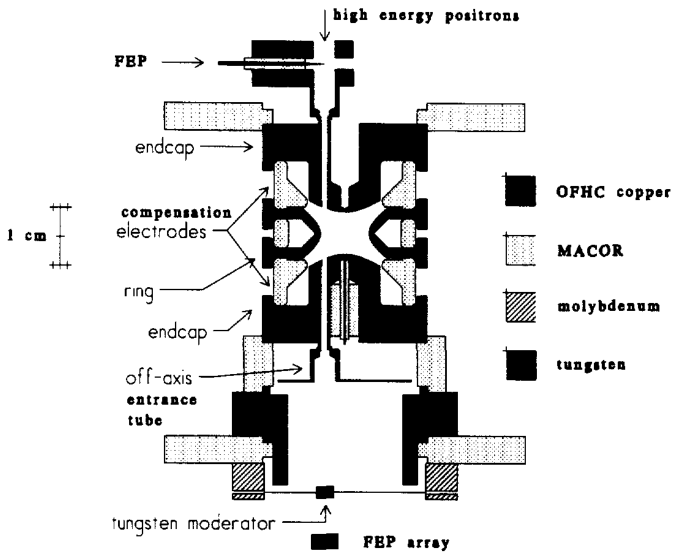

Figure 4: Penning trap and moderator for trapping of positrons.

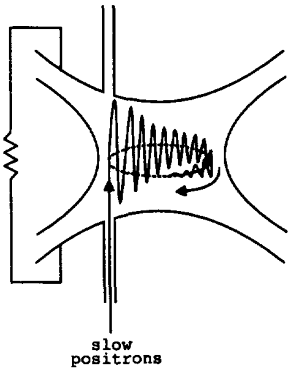

Figure 5: Exaggerated view of the trajectory of a slow positron which enters the trap, and makes axial (vertical) oscillations of decreasing amplitude (due to the electrical damping) as the positron circles in a magnetron orbit. Small cyclotron orbits are not visible.

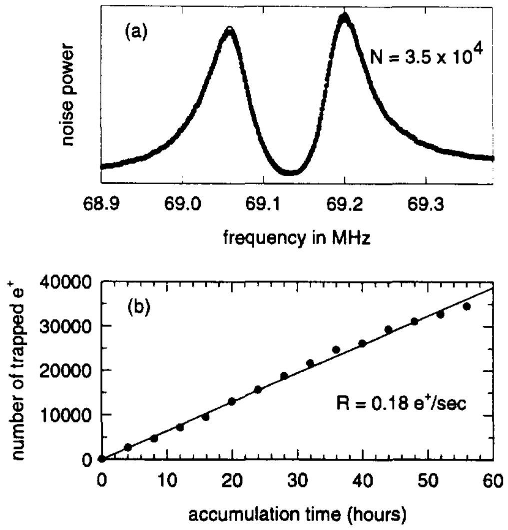

Figure 6: (a) Measured noise spectrum across the RLC damping circuit (dots) is fit (solid curve) to determine the number of trapped positrons. (b)Number of trapped positrons vs. accumulation time.

remain in the trap indefinitely if the energy loss is sufficient to prevent their leaving through the entrance hole.

The number of positrons is determined from the frequency spectrum of the voltage across the resonant RLC circuit. Without positrons in the trap, a resonance is observed at the resonant frequency of the circuit, due to the random thermal (near 4 K) motions of the electrons in the circuit. When positrons are added, they effectively "short" the noise signal, producing a pronounced dip as illustrated in Fig. 6a. The number of trapped positrons is determined by fitting this dip and comparing to electrical signals observed with one through five trapped positrons. Fig. 6b shows how the positrons accumulate linearly in time.

A high positron density is desired since the antihydrogen recombination rate depends either linearly or quadratically upon the positron density, depending on the recombination process. The observed density is nearly $10^8/\mathrm{cm}^3$. The density depends primarily upon the size of the trap and upon the potential difference across the trap electrodes, making it more difficult to attain the desired high densities in a large trap. The achieved density is more than adequate for antihydrogen production. Nonetheless, experiments are underway to obtain more trapped positrons in order to fill a larger volume with positrons at the observed density. It would also be convenient if the positrons could be loaded more rapidly.

3.3 More cold positrons

The most straightforward way to increase the number of trapped positrons is to increase the size of the radioactive source used to produce them. This approach, limited primarily by safety concerns, is being pursued by the Trap Collaboration (PS196) with ^{58}Co for experiments planned to take place at LEAR at the end of 1996. We are also trying to damp positrons with cold electrons in a nested trap, but do not expect this will give a high capture efficiency. A more efficient positron accumulation would allow more positrons to be accumulated more rapidly with less concern about safety. To this end, one group in our collaboration is testing a room temperature apparatus to capture positrons which collide with laser-cooled ions in a a trap [18, 19]. After summarizing this approach, we will mention other possibilities.

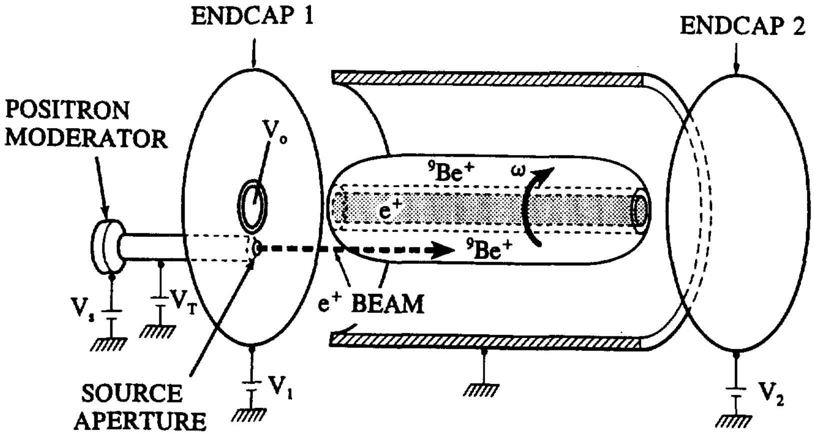

Figure 7: Positrons will be trapped via collisions with laser cooled ions.

Positrons are only captured into a trap if their motions are damped while they are traveling through the trapping well. The positrons of the previous section were damped electronically. The damping of positrons via their collisions with a long (> 5 cm) and dense (> 10^9 cm^{-3}) plasma column of laser-cooled $^9Be^+$ ions promises a much higher efficiency [18]. For positrons that are first moderated in a crystal, the trapping efficiency could approach 10%. Both species are positively charged and hence can be stored in the same potential well. Final temperatures should approach 1 mK (axial energy). Collisional cooling of $^{199}Hg^+$ ions stored with laser-cooled $^9Be^+$ ions has been observed, as has the cooling of $^9Be^+$ simultaneously stored with laser-cooled Mg^+ ions [20]. Collisional cooling of simultaneously trapped ions is sometimes called "sympathetic cooling".

The basic idea is illustrated in Fig. 7. We assume that $^9Be^+$ ions are first loaded into a Penning trap and laser-cooled by established techniques. With only $^9Be^+$ ions in the trap, the ions form a uniform density, nonneutral ion plasma (temperature $T(^9Be^+) \approx$ 10mK) which rotates about the trap axis at frequency ω. We will assume the Debye length for the plasma is small compared to its dimensions. Therefore the potential inside the plasma is independent of the axial coordinate. We assume that positrons from a moderator are injected through an (in general) off-axis aperture in one endcap (endcap 1) with just enough energy to pass through the center of the aperture. The potential at the center of the aperture is less than the potential V_1 of endcap 1 because of the proximity of the tube (held at potential $V_T < V_1$) between the moderator and endcap 1. The diameter of the $^9Be^+$ plasma is assumed to be large enough that the incoming positrons pass through the $^9Be^+$ ion plasma. The other trap endcap (endcap 2) is biased at a potential V_2 which is sufficient to reflect the positrons back through the $^9Be^+$ plasma. Positrons inside the $^9Be^+$ plasma also rotate about the trap axis at approximately frequency ω. If ω is large enough and/or the $^9Be^+$ plasma is sufficiently long, the positrons will have been displaced azimuthally when they approach endcap 1 from inside the trap and will be reflected by the potential V_1 back through the $^9Be^+$ plasma. As the positrons pass through the $^9Be^+$ ions they undergo Coulomb collisions which extract axial energy from them. At the low energies we consider, positron annihilation by collisions with the $^9Be^+$ ions is suppressed by Coulomb repulsion. Initially, the positrons' axial energy is primarily transferred into their cyclotron motion energy since the recoil energy of the $^9Be^+$ ions is small. If these collisions extract enough axial energy before the positrons encounter the entrance aperture again, they will be trapped. If the entrance aperture is mounted off axis, the positrons can make many oscillations along the trap axis (and through the $^9Be^+$ ions) before encountering the entrance aperture again.

Once trapped, the positrons cool by cyclotron radiation and collisional, sympathetic cooling with the cold $^9Be^+$ ions. When sufficiently cooled, the positrons coalesce to a uniform density plasma column along the trap axis which co-rotates with the $^9Be^+$ plasma (both at frequency ω) as shown in Fig. 7. At low temperatures, the $^9Be^+$ plasma separates from the positron plasma forming an annular region outside the positron plasma. Qualitatively, the separation occurs because of the larger outward centrifugal force on the $^9Be^+$ ions. The positron cyclotron motion is strongly coupled to the ambient temperature (4K assumed here) by cyclotron radiation. At temperatures below about 10K, the positron axial motion decouples from the cyclotron motion and we expect the positron axial or "parallel" motion temperature $T_{||}$ to be reduced to less than 4K by the Coulomb interaction with the cold $^9Be^+$ ions. Therefore we expect the parallel temperature $T_{||}$ to be lower than the cyclotron or "perpendicular" temperature $T_{\perp}$. For ω less than half of the ions' cyclotron frequency, the positron and $^9Be^+$ plasma densities will be approximately equal and limited by the maximum attainable $^9Be^+$ plasma density (Brillouin density). Here we will make the approximation $n(e+) \approx n(9Be^+)$. Since the Brillouin density for an ion species of mass M scales as B^2/M where B is the magnitude of the Penning trap magnetic field, we want B as large as possible and M as small as possible. This is the reason for choosing $^9Be^+$ ions. Other ions would work in the scheme described here, but $^9Be^+$ has the smallest mass of any of the positive ions which can be easily laser cooled, therefore giving the highest density ($n \approx 10^{10}$ cm^{-3} for $B = 6$ T).

There are at least two other approaches to positron loading that we will not pursue initially. The first is to capture positrons that cool via collisions with a background pressure of neutral atoms introduced into the trap. This scheme is attractive because of the large number of positrons which have been trapped in this way [21, 22]. The challenge is to introduce enough differential pumping to get the pressure to the extremely low value needed to avoid the annihilation of antihydrogen. A minimum requirement thus seems to be a substantial, room temperature apparatus outside the cryogenic environment needed to allow the confinement and study of cold antihydrogen. We prefer to avoid this if possible, but will reconsider if we are dissatisfied with the number of positrons which we accumulate by the methods described above. The second alternative is to slow and capture positrons from electron-positron pairs produced at an accelerator. (We understand that such studies are being planned at the Aarhus microtron.) The attractive feature of this scheme is the possibility to trap large numbers of positrons quickly. The disadvantage is the need to add a very substantial and expensive facility to an already complicated apparatus. It seems prudent to investigate the simpler positron accumulation schemes while awaiting a demonstration of efficient accumulation of microtron positrons into a cryogenic vacuum.

4 Producing and Observing Cold Antihydrogen

4.1 Recombination Processes

Before and during the time that the TRAP Collaboration (PS196) was developing the techniques to cool and accumulate 4 K antiprotons, members of the collaboration were already considering the production of cold antihydrogen from cold antiprotons and positrons accumulated in separate traps [14, 13]. To recombine, a positron and antiproton must have sufficient kinetic energy to approach each other. This energy must be removed to form an atomic bound state. Energy and momentum cannot be conserved unless a third particle is involved. Different processes have been considered, including radiative recombination, stimulated radiative recombination, a three body recombination, and a recombination process involving positronium. We look briefly at each of these in turn.

Radiative recombination can be thought of as producing an excited hydrogen atom which radiates a photon to conserve energy and momentum.

$$\bar{p} + e^+ \rightarrow \bar{H} + h\nu \tag{1}$$

This process suffers from a low rate because it takes approximately a ns to radiate a photon, much longer than the duration of the interaction of the $\bar{p}$ and an e^+, even if these particles have an energy corresponding to 4 K. For 10^6 antiprotons at 4 K within a 4 K positron plasma of density $n_e = 10^8/cm^3$, the estimated recombination rate [13] is 3×10^3/s. The radiative recombination process has the attractive feature that most of the antihydrogen formed would be in the ground state, but the anticipated rate is lower than for other processes.

The radiative recombination rate can be considerably increased by stimulating the process with a laser.

$$\bar{p} + e^+ + h\nu \rightarrow \bar{H} + 2h\nu \tag{2}$$

Laser-stimulated, radiative recombination has been observed in merged beams [23, 24], but has not yet been observed in a trap. Under realistic conditions in a trap, the laser should increase the radiative recombination rate for the production of antihydrogen in the ground state by up to a factor of 10^2 [13]. The laser intensity cannot be increased arbitrarily to speed the recombination because the cross section for field ionization increases sharply at high intensities. There is also the suggestion [13] to use a CO_2 laser to stimulate recombination to principal quantum numbers $n = 10$ (or to nearby levels with various diode lasers), rather than to the ground state. The advantage is an additional increase in rate over unstimulated radiative recombination by a huge factor of 10^5 for the antiproton number and positron density mentioned above, provided that sufficient laser power is available and can be managed within the cryogenic environment. We intend to pursue the stimulated radiative recombination process.

The three body recombination

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+ \tag{3}$$

is attractive because the recombination rate promises to be much higher than for any other processes [13]. However, it is highly excited states that are rapidly produced and the deexcitation to lower states takes longer [25]. For 10^6 antiprotons at 4 K, submerged within an extended plasma of 4 K positrons at density $10^7/cm^3$, the recombination rate is an astounding 10^9/s [13]. A strong magnetic field (for the trap containing antiprotons and positrons) would reduce this high rate [26] by approximately a factor of 10, and an electric field (also part of the traps) has some effect [25], but the rate still seems higher than for other recombination processes. The related process

$$\bar{p} + e^+ + e^- \rightarrow \bar{H} + e^- \tag{4}$$

has also been mentioned [13], but this seems more difficult to arrange.

Radiative recombination with and without laser stimulation will be attempted in both a nested Penning trap and in a combined Penning-Paul trap (discussed in the next section). The nested Penning trap also offers some control over the three body recombination process. An antihydrogen atom leaving the trapped positron plasma will experience an electric field whose magnitude can

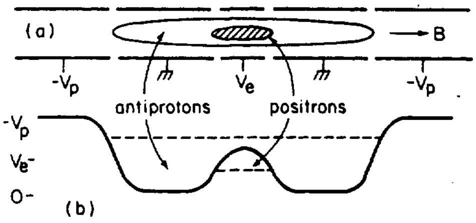

Figure 8: Nested Penning trap should allow antiprotons and positrons to interact at low relative velocity, where the recombination rate is largest.

be adjusted. This field will ionize atoms which are highly excited. For example, an electric field of 7V/cm will ionize all the antihydrogen produced with principal quantum number $n > 100$, returning the positron and antiproton to their respective wells. With a strong electric field the radiative recombination can thus be "switched off" entirely (to investigate radiative recombination, for example). With a carefully adjusted field, three body recombination to the lowest possible states can be selected. There is also the possibility to analyze the excited state distribution in the hope of designing an experimental procedure to deexcite these states as rapidly as possible.

The last recombination process uses positronium, the bound state of an electron and a positron, with the electron carrying off the excess energy [27].

$$\bar{p} + e^+e^- \to \bar{H} + e^-. \tag{5}$$

One advantage of of this process is that the antihydrogen is produced preferentially in the lowest states. Also when antiprotons are not available, the charge-conjugate process can be studied (recombining protons and positronium to form hydrogen and positrons). This was recently observed [28] using beams of protons and electrons. Unfortunately, comparable quantities of antiprotons and positrons are very difficult to arrange. It should be possible to increase the recombination rate by initially exciting the positronium atom with a laser [29]. Nonetheless, the disadvantages of the recombination using positronium is that the projected rate is extremely low for realizable numbers of antiprotons, and existing postronium beams. It may be possible to make a miniature positron storage ring to greatly increase the available positronium. However, the apparatus required is somewhat different than is required for the other processes and we thus do not plan to initially pursue this approach.

Much experimental investigation is still required to determine the most efficient route to low energy antihydrogen. We will initially investigate radiative recombination (Eq. 1), stimulate this process with a laser (Eq. 2), and attempt to characterize and control the three body recombination (Eq. 3).

4.2 Interacting Electrons and Protons

The nested Penning trap (Fig. 8) was initially proposed [13] as a promising way to make antiprotons and positrons interact at the low relative velocities where the recombination rates are highest. While recombination has not yet been observed in a nested Penning trap, the interaction of cold electrons and protons with extremely low relative velocities has now been clearly demonstrated by members of our collaboration [30]. Fig. 9a shows the energy spectrum of hot protons when there are no electrons in the inner well. (Highest energies are to the left because the highest energy particles are detected first.) When electrons are introduced into the inner well, they rapidly cool via synchrotron radiation to come into thermal equilibrium with their 4K surroundings. The protons slow as they climb the potential hill to enter the cloud of electrons, then lose energy via collisions with the electrons. This process continues until the protons lose just enough energy to keep them from entering the electron cloud again. The cooled protons thus reside in the two side wells, decoupled from the electrons in the center well.

An example of the resulting energy spectrum of the cooled protons residing in the side well to the right is shown in Fig. 9b. The measured energy is with respect to the bottom of the side wells. It should be stressed, however, that the relative velocity of the trapped protons and electrons is what is important, not the energy of the cooled protons with respect to the bottom of the side well. This relative velocity of protons and electrons is extremely low when the cooling stops. We would thus expect recombination to be triggered when the depth of the electron well is reduced slightly to make the protons and electrons interact again at low relative velocity. Fig. 10 illustrates that the protons always cool to have the lowest possible velocity with respect to the cold electrons. The measured proton energy with respect to the bottom of the side wells, corrected for adiabatic cooling, is shown as a function of the depth of the central electron well. The straight line represents the protons cooling to the energy of the electrons (very near to the bottom of their well), where the relative velocities of the protons and electrons are very low.

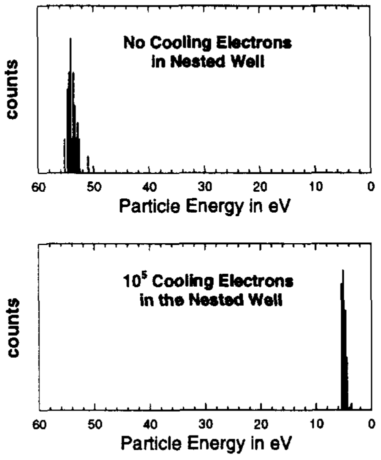

Figure 9: Number versus energy of hot protons (above) and cooled protons (below) within a nested Penning trap.

The demonstration of the nested Penning trap, in which protons are cooled to low velocities relative to the cooling electrons, took place in the extremely good cyrogenic vacuum required to avoid annihilating antihydrogen. In fact, the 4K apparatus used was virtually identical with apparatus used by the TRAP Collaboration (PS196) for the low energy antiproton experiments.

An alternative approach to getting protons and electrons to interact is to store protons in a Penning trap, and to store electrons in a superimposed Paul trap. Ions have been confined in Paul traps that were run in such a combined mode since the early days of particle trapping, with an application to protons and electrons analyzed more recently [31]. The simultaneous confinement of electrons and ions (1/8 were protons) in the combined trap of Fig. 11 was recently demonstrated by members of our collaboration [32]. Several thousand electrons and ions were confined at the same time. The interaction of the electrons and ions was observed insofar as the presence of electrons reduced the number of ions which could be stored in the trap, presumably due to the heating of the electrons by the microwave driving field used to confine them. This heating is expected to increase with increasing electron number, so the full effect of the heating will now be studied to see how it can be managed. The hope is to soon repeat the experiment with only protons and electrons, after heating out the heavier ions. When electrons and protons are confined simultaneously, laser-stimulated, radiative recombination to $n = 10$ will be attempted with a CO_2 laser [13]. The demonstration apparatus had a pressure of 10^{-8} Torr, but there are plans to develop and test a cryogenic apparatus which has the extremely low pressure required to avoid annihilating antihydrogen atoms.

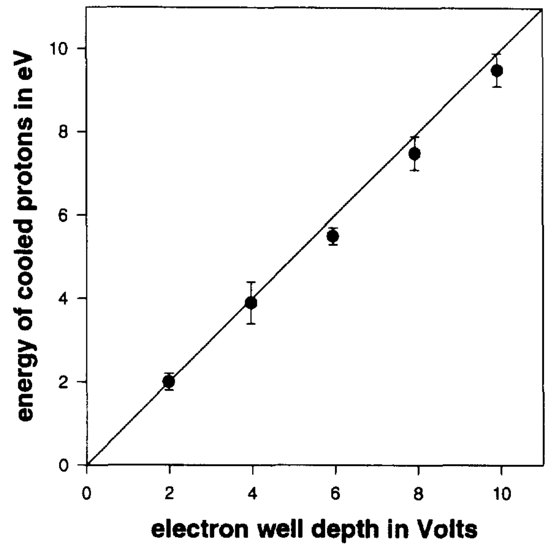

Figure 10: Measured proton energy above the bottom of trap as a function of the depth of the central electron well in a nested Penning trap. A straight line corresponds to the protons cooling to the level of the highest energy electrons. That is, the protons cool so that they have the lowest possible velocity relative to the cold electrons.

Both the nested Penning trap and the combined Penning-Paul trap environments are now being studied in more detail by members of the collaboration. The antihydrogen apparatus will be constructed to allow either type of trap to be readily inserted so that the best alternative can be utilized when antiprotons again become available.

4.3 Real Time, Imaging Antiproton Annihilation Detector

The goal of these antihydrogen experiments is to eventually observe the cold antihydrogen that is produced, and in fact to perform extremely accurate spectroscopic measurements with antihydrogen atoms. Enroute to this goal, it will be extremely useful to be able to image any annihilations of antiprotons and antihydrogen atoms in real time. This crucial diagnostic will allow optimizing the production of cold antihydrogen sufficiently to permit the optical observations and measurements.

When an antiproton annihilates with a proton in a surface it produces high energy, charged pions. By detecting the charged pions in a multilayer structure with sufficient spatial resolution, it is possible to reconstruct the impact point of the antihydrogen with the surrounding trap walls, where the annihilation takes place. With such a reconstruction of the vertex from the charged pions, it seems feasible to distinguish annihilations at the center of the trap (where there should be no annihilations) from those occurring at the walls. Ideally, the 511 keV photons from the annihilating positron would be detected in coincidence.

Other requirements of the experimental setup significantly complicate the design of the imaging detector.

1. The available space for such a detector setup is very limited by the small inner diameter of the superconducting solenoid which generates the strong (6 T) magnetic field for the Penning trap.
2. Some detectors (e.g. photomultipliers) will not work in the high magnetic field.

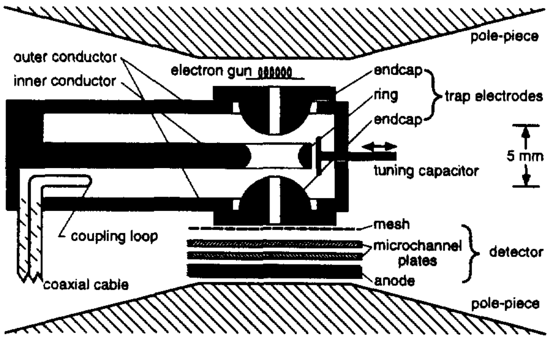

Figure 11: Combined Penning - Paul Trap used to confine positive ions and electrons, along with the detector and electron gun. Semispherical electrodes connected to a resonant coaxial line generate dc and microwave quadrupole fields. The magnetic field is produced by permanent magnets whose pole pieces are displayed. Optical access to the trap's center is not shown in the figure.

3. Some detectors are not constructed to operate at either 4.2 or 77K, the temperature of the trap and its surroundings.
4. The mass of material within the solenoid and its dewar (roughly equivalent to 6 cm of copper) prevent detecting the annihilation gammas from the positrons with an detector in the low field region outside the magnet and dewar.
5. This same material introduces a fairly large multiple scattering for the charged pions, making it difficult to reconstruct the annihilation vertex with an external detector.

The design of the imaging, annihilation detector is still being actively considered. A partial cross section of one option we are considering is represented in Fig. 12. To simplify, it does not provide the vertical position of the vertex, along the direction of the magnetic field. A three layer silicon strip vertex detector surrounds the enclosure of the Penning trap within which cold antihydrogen will be produced. We are also investigating the possibility to use a layer of BGO crystals between the silicon strips to detect the 511 keV photons. (Detailed studies of the background 511 keV photons produced as the charged pions traverse material are planned.) Outside of the magnet dewar, a layer of large plastic scintillators will be used to detect the charged pions passing through the magnet to provide the main trigger.

In this preliminary study, we consider three silicon strip detectors mounted on cylindrical support structures with diameters of 10, 12 and 16 cm. The support cylinders are kept aligned by appropriated spacers and end flanges so that the detector unit can be inserted from the top of the magnet with good thermal contact to the magnet bore at 77K. The final choice of the specific type of strip detectors is not yet made, but preliminary calculations are done on the basis of the sili-Detectors used and operated in the vertex detector of the Crystal Barrel Experiment [33, 34]. These counters have an active area of 80 mm x 8 mm with 128 strips (pitch 0.05 mm, strip width 0.0015 mm). The Viking readout chip for the serial readout is bonded directly onto the strips of the counters to get a very good signal to noise performance. The serial readout reduces the number of readout cables which can then be routed to minimize noise picked up in the readout electronics. Sixteen strip counters can be handled by one VME-Readout module (Sirocco), and the 144 needed counters are readout by 9 modules.

Preliminary estimates suggest that a spatial resolution of 50 micron in silicon strip detectors allows a reconstruction of the annihilation vertex with an error of ±1.5 mm. The detection efficiency for charged pions in the momentum range of 100 to 900 MeV/c is nearly 100%, and the solid angle acceptance varies between 30% to 25% of 4π, depending on the longitudinal position of the annihilation vertex.

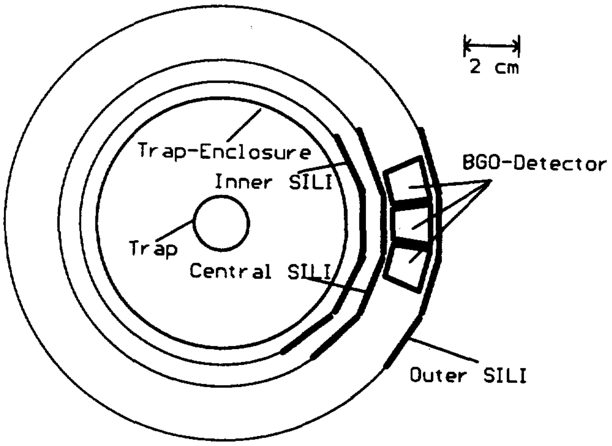

Figure 12: Partial cross section of an imaging annihilation detector under study.

To get a fast trigger signal from the strip detectors we would pick up the induced signal from the common backplane layer of the strip detectors via a low noise amplifier and discriminator. This technique was already demonstrated by the Crystal Barrel detector setup. It allows a determination of the event multiplicity in the strip detectors, which can be used in the trigger setup to select specific event topologies. Signals from the central layer could be used to identify hits in the BGO crystals as gammas, if these signals are implemented as a veto. We are investigating the possibility to segment the common backplane of the strip detectors in three or for areas, each connected to a separate amplifier/discriminator channel to gain coarse information on the vertical position of the annihilation vertex. However, space restrictions and the heat load from the additional electronics seem to severely limit the longitudinal segmentation of the counter backplane to a few channels.

The detection of the 511 keV gammas from the coincident positron annihilation would be done in a segmented barrel of 32 BGO crystals. Each crystal would thus have a length of 80 mm and a trapezoidal cross section (thickness of 13 mm, inner width of 12 mm, and outer width of 15 mm). Such a structure would fit in between the central and outer Silicon strip detector barrel. It would be also mounted on a cylindrical support structure to so that crystals and strips would together form a compact insert into the bore of the magnet. The readout of the light will be done on both ends by photo avalanche diodes, which have reasonable gain (1000) and work in the high magnetic field. About 50% of the 511 KeV gammas will deposit their energy completely in this type of crystal. The geometrical solid angle is also about 25 to 30%, but will be reduced by the coincident passage of the charged pions through the crystals. Crystals hit by a charged track will not be able to identify an annihilation photon owing to the large (11.7 MeV) energy deposit by the pion. Also, the conversion probability for the gammas from the decay of neutral pions is comparable with the stopping power for the 511 KeV gammas. For a typical annihilation of the antiproton into 2 charged and 2 neutral pions, the solid angle drops to 20 to 24% of 4π. Therefore the possibility to trigger on the multiplicity in the silicon detectors and the BGO crystals is essential to enhance the number of events where the 511 KeV gammas can be clearly identified. The hit pattern in the BGO crystals and the energy deposit will be recorded with conventional CAMAC ADC-modules and pattern units.

The coincident detection of the annihilation products from the antihydrogen in the compact environment of a antihydrogen formation experiment with Penning traps is a challenging task. The illustrative design suggests the possibility of a detector based on standard techniques used in high energy particle detectors. No new conceptual research and development seems necessary. Simulations of the complete detector setup with the GEANT Monte Carlo program are needed to evaluate exact numbers for the detection efficiency of the setup before an optimized final layout can be realized.

5 Laser Cooling and Spectroscopy of Cold, Trapped Antihydrogen

5.1 Laser Cooling

The interest in the formation of antihydrogen stems primarily from its use as a testing ground of fundamental physics, namely precision spectroscopy to test CPT invariance. Though a CPT test has been the focus of this Letter, we are also intrigued by the possibility to make a direct measurement of the gravitational acceleration of antihydrogen for the first time. This promises to be very difficult insofar as the weakness of gravitational forces on individual antihydrogen atoms requires extremely cold atoms to produce a measurable gravitational effect [7]. The gravitational potential energy for a displacement of 1 meter only corresponds to a thermal energy of 1 mK. The spatial distribution of antihydrogen atoms trapped in a reasonably-sized magnetic trap, for example, would show a marked effect due to gravity, only if the atoms can be cooled to the mK temperature range.

Laser cooling is the best candidate to produce such low temperatures as needed for experiments with trapped antihydrogen, given the expected low densities available and the difficulty imposed by annihilation on surfaces. It offers a means to extract energy from antihydrogen atoms in a dissipative fashion, but without the danger of producing annihilation, or by relying on atomic collisions present in very high density samples.

The expected limit to laser cooling (Doppler limit) is about 3 mK [35], which would be sufficient for such experiments. (The spectacular μK temperatures that have been achieved with laser cooling in other atomic systems would not be available due to the large recoil energy associated with the emission of an energetic photon and light atom in this system.)

Laser cooling of (anti)hydrogen is challenging, primarily due to the difficulty of the production of the required amounts of narrow-band Ly-α radiation at 122 nm. The bandwidth of the Ly-α radiation should be equal to or preferably less than the natural line width of the transition, 100 MHz. Lasers at this vacuum ultraviolet wavelength are not available, so the light has to be generated with non-linear mixing techniques, such as tripling or four-wave mixing in gases [36]. Such processes are very inefficient, resulting in modest numbers of photons produced. Typical results, achieved by members of our collaboration and elsewhere, are 10^9 photons/ pulse for ns pulses with repetition rates of 10-100 Hz. Such a system has been used by one group in our collaboration to laser cool a sample of magnetically trapped hydrogen [37]. In this case they started with a sample cooled to 80 mK by contact with the walls of a dilution refrigerator (not a possibility with antihydrogen). Laser cooling allowed them to further cool to 8 mK, slightly above the theoretical limit of 2.4 mK. This limit should be approachable in a low density sample, as would be the case with antihydrogen. They also demonstrated a technique called light induced evaporation which used Ly-α radiation to selectively evaporate hot atoms, but this technique is not likely to be applicable, since it relies on the strong thermalization that occurs with a high densities of atoms.

Laser cooling trapped antihydrogen is quite feasible, and is essentially no more difficult than cooling hydrogen. The long trapping times demonstrated with hydrogen allows the use of existing low power laser systems with low repetition rates. The more challenging task is to use laser cooling to cool a sample of antihydrogen produced from recombination from a cryogenic positron/antiproton plasma at 4K. This will require the generation of a long pulse (or train of many short pulses) of Ly-α radiation, sufficient to decelerate the antihydrogen to an energy low enough to be magnetically trapped (about 1 K for an optimally designed magnetic trap). The antihydrogen atoms would be decelerated in a short distance of much less than 1 mm, with each atom scattering approximately 100 photons in the 1 μs pulse. Nonetheless this system presents a challenge to optical and laser technologies. Various promising schemes have been proposed, based on extensions of the systems already demonstrated, and the rapid evolution of laser science and materials is most encouraging. Experimental efforts to produce improved Ly-α sources will be restarted when it is known that low energy antiprotons will be available after 1996.

5.2 Spectroscopy

Initially, the precise spectroscopy of antihydrogen will be carried out with small numbers of antihydrogen atoms confined in a magnetic trap. How feasible is such an endeavor? As an answer, we consider the spectroscopy of the 1s-2s transition of a thousand antihydrogen atoms in a magnetic trap [38]. Their average energy is 80 μeV, corresponding to a temperature of about 1 Kelvin. A tunable standing wave laser field illuminates the entire trapping volume and excites the atoms to the 2s state. The energy of the ground state and the 2s state increases with the magnetic field almost at the same rate such that the transition frequency is only shifted a very small amount. Only a small relativistic correction of 180 kHz/T gives raise to a line broadening due to the inhomogeneous magnetic field in which the atoms are trapped. The atoms are detected by applying a microwave drive which induces a transition to the $2p3/2$, $m_L = 1$, $m_s = 1/2$ state from where the atoms decay rapidly into the initial ground state. The emitted Ly-α photons are counted with a photomultiplier tube located out of the strong magnetic field. The limiting factor is the ionization of excited atoms by absorbing an additional photon from the standing wave. As a result, each atoms may undergo only a limited number of excitation cycles until it is destroyed. The number of photons each atom can scatter only depends on the ratio of the detection rate and the ionization rate.

If we assume that the signal to noise ratio is shot noise limited, the spectral resolution ν is given by $\nu = \Delta/\sqrt{q}$, where "q" is the total number of scattered photons, and Δ is the instrumental line width which is dominated by the relativistic Zeeman broadening. To maximize q we chose the detection rate as large as possible but not faster than the instrumental linewidth in order not to broaden the line by the detection itself. The ionization rate should be as small as possible which implies a preference for small light intensities. A lower limit for the intensity is given by the time t during which the apparatus may be reliably operated. During this time the trap contents should be "used up" and a major fraction of the trapped atoms should have been ionized. A detailed calculation (for N trapped atoms and a Ly-α detection efficiency ϵ) results in a spectral resolution

$$\nu = 1.7 \frac{\Delta^{5/6}}{t^{1/6}(\epsilon N)^{1/2}}.$$

With 1000 atoms trapped initially, a detection efficiency of 0.5%, a measurement time $t = 5$ min and an instrumental linewidth of 50 kHz, the resonance line may be split to within 2 kHz corresponding to a relative uncertainty of 2 parts in 10^{12}. The necessary light intensity of 60 W/cm^2 is achieved with 100 mW circulating power and a beam waist radius of 330 micron. This estimation also shows that the resolution is most effectively improved by reducing the instrumental linewidth (i.e. the Zeeman broadening) rather than increasing the measurement time or the number of trapped atoms.

In principle the Zeeman broadening could be eliminated with a box shaped trapping potential since the atoms "see" the magnetic field only during the infinitesimal short moments when they are reflected at the potential walls. This situation may by approximated with a trapping potential which is established by a high order multipole field. If, in addition, the laser beam waist is slightly smaller than the atom cloud the atoms get excited in a region where the potential is essentially flat and the Zeeman shift negligible. In an octupole trap whose volume is illuminated to one third and filled with atoms up to a magnetic field of 1 T the instrumental line width is reduced to 560 Hz and the spectral accuracy of the measurement is improved to parts in 10^{14}. A similar instumental linewidth could be achieved with a conventional magnetic trap if the atoms are cooled down to the mK range, by laser cooling for example.

The above estimates are only one illustrative scenario for antihydrogen spectroscopy. We expect that the actual experiments will begin with less accurate optical observations of antihydrogen, probably making use of a Ly-α driving field. The next step in pursuit of higher precision will likely use a near resonant, two photon excitation process with one of the drive photons being a Ly-α photon. Two photon spectroscopy of the 1s - 2s transition should follow. If excited states of antihydrogen are produced, it may be attractive to do the spectroscopy of other excited states. The actual progression of measurements depends upon the number of antiprotons which will be trapped, and upon what we learn about the spectroscopy of small numbers of atoms. Once CERN is committed to providing antiprotons beyond 1996, one group in our collaboration will begin a serious effort to demonstrate accurate spectroscopic measurements with small numbers of trapped hydrogen atoms.

6 Conclusion

Our expanded collaboration is determined to produce low energy antihydrogen, and to compare it to hydrogen at extremely high accuracy. We bring a broad range of experience and expertise to this problem insofar as most of us have invented or contributed substantially to one or more of the crucial techniques needed to make and study cold antihydrogen. However, the project is extremely difficult and thus represents a significant challenge. We have accumulated many cold antiprotons and positrons in ultrahigh vacuum, but more of these ingredients are desired. We have made electrons and protons interact with a very low relative velocity, but may not reach the conditions required to observe cold antihydrogen until we take advantage of the high detection efficiency that is possible with antiprotons and positrons. We have trapped extremely cold hydrogen but only after cooling the hydrogen in a way that is not applicable to antihydrogen. We have carried out extremely accurate spectroscopic measurements with hydrogen, but not yet with a small number of atoms. Careful coordination will be required to make sure that the many traps, lasers, and detectors do not perturb either the slowly moving particles or each other.

In some ways the situation is similar to the situation which pertained when the original TRAP Collaboration (PS196) proposed to accumulate antiprotons at an energy 10^{10} times lower than the lowest storage energy in the Low Energy Antiproton Ring, and to listen to the radio signal of a single antiproton as a way of comparing antiproton and proton 45,000 time more accurately than had been done before. Despite the experience and expertise of the original collaboration, techniques demonstrated with matter particles had to be adapted for the very different circumstances under which antimatter particles were available. Much had to be invented, but after a decade of concentrated effort by a small team, the ambitious goal was met and even substantially exceeded.

When the SPSLC and CERN commit to providing the 100 MeV/c antiprotons via the Antiproton Decelerator, the Antihydrogen TRAP Collaboration (ATRAP) commits its experience, expertise and resources to a professional and determined pursuit of the extremely accurate spectroscopy of cold antihydrogen.

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