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# The Production and Study of Cold Antihydrogen

## The Annual Progress Report by the Antihydrogen TRAP Collaboration (ATRAP)

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# A. Overview

## 1. Introduction

The ATRAP Collaboration is privileged to work at the unique AD facility – the only place in the world with the capability of producing the low energy antiprotons needed for antihydrogen experiments. We are grateful to the SPSC for its efforts to facilitate this research, and to the rest of the CERN community for making this possible.

The motivations (p. 4) and milestones (p. 9) for ATRAP's antihydrogen research remain exactly the same as initially proposed, and then endorsed by the SPSLC, at the outset of the AD program at CERN. In fact, these long-term antihydrogen research motivations, goals and milestones were the central motivation for CERN's decision to build the Antiproton Decelerator.

The backdrop for this year's beam run is the incorporation of our first generation Ioffe trap, within which we hope to trap cold antihydrogen atoms, into the ATRAP apparatus. The crucial first question was whether the antiprotons would remain stored long enough so that antihydrogen could be produced. Our encouraging positive answer to this question was reported in PRL [1]. The next step was to produce antihydrogen atoms within a Penning-Ioffe trap – an important milestone that was also reported in PRL [2]. The current goal is to produce atoms that are cold enough to be trapped, and to observed trapped antihydrogen atoms.

The 2009 beam run showed steady progress but no spectacular results. We hope to build directly on most of the advances during 2010.

- We verified the observation that we made at the very end of the 2008 beam run, that we could produce electron and positron plasmas that were at 1.2 K rather than the 7 K that we first realized in our ATRAP II apparatus. This is a very significant advance towards the production of antihydrogen atoms that are cold enough to trap. We also greatly improved our ability to rapidly measure plasma temperatures. We are still sorting through the conditions under which the low plasma temperatures can be realized, and hope to publish the result this year.

- We succeeded in observing single antiprotons in our trap at the end of the 2008 antiproton run, demonstrating the detection sensitivity needed to search for antihydrogen ion production. We hoped to continue these studies during 2009 but did not get to this.

- We spent considerable time this year increasing the number of trapped antiprotons that were available for antihydrogen formation experiments. At the end of 2008 we had large numbers of antiprotons trapped in our apparatus but we lost a substantial fraction of these as we transferred them out of the higher field trapping regions and into the low field region where our Ioffe trap is located. We were eventually able to eliminate most of the antiproton losses, and are hopeful that we will soon be able to speed up the process. We are delighted to report that we can now accumulate as many as 5 million low energy antiprotons in about an hour.

- We spent time investigating direct measurements of the temperature of the antiprotons without and with added cooling electrons. We have directly measured temperatures as low as about 40 K. Investigations to determine whether this is a real temperature or a limit of our measurement method will continue during this year.

- With the larger number of trapped antiprotons we continued our search for trapped antihydrogen atoms, a search at higher sensitivity than what we reported first back in 2008. Quenching our Ioffe trap continues to work, but we look forward to being able to use our second generation Ioffe trap.

- We tried hard this year to make antihydrogen via laser-controlled charge exchange method that we demonstrated some time ago in a much smaller trap with many fewer positrons and antiprotons. Our improved laser systems worked well, and we successfully sent laser-excited Rydberg Cs atoms through the larger trap. However, we discovered that the larger trap required more Cs atoms than our sources we able to deliver, and we encountered a heating mechanism for the large number of trapped antiprotons that was not observed in our smaller traps with fewer trapped antiprotons. Pursuing these studies with larger Cs sources that recently became available will be an important priority during 2010.
- The coils for our second generation Ioffe trap are now complete. We hope to complete the assembly this spring. Because the new apparatus has substantial advantages, we are trying very hard to get this new apparatus into service this year.
- A new refrigerator-cooled insert dewar has been completed and is in what seems likely to be the final week of testing. This second dewar should make it possible for us to switch our apparatus in a couple of days instead of what is now about two weeks during which we cannot take antiprotons.

## 2. Motivations

As mentioned, the motivations are the same as was outlined in the original ATRAP proposal. Experimental tests have made physicists abandon earlier assumptions – first, that reality is invariant under P transformations and then, that reality is invariant under CP transformations. The current assumption, that reality is invariant under CPT transformations, is based in large part upon the success of quantum field theories. These are invariant under CPT as long as reasonable assumptions (like causality, locality and Lorentz invariance) are made. Of course, gravity has not yet fit into a quantum field theory. Theoretical investigations of possible CPT violations have thus appeared in the context of string theory [3, 4], and as related to possible violations of Lorenz invariance [5].

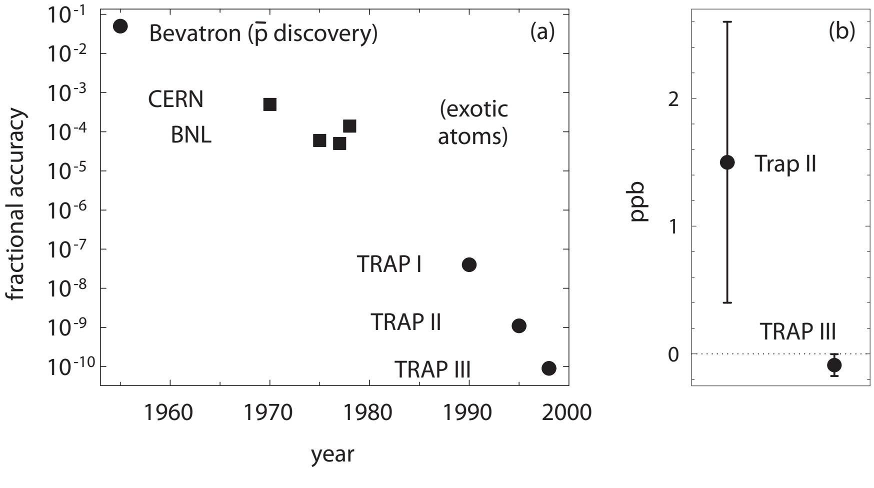

Figure 1: The accuracy at which antiprotons and protons have been compared [6].

However, whether CPT invariance is actually conserved is an experimental question. An improved CPT test is a primary motivation for experiments which compare antihydrogen and hydrogen. A reasonable requirement of a new CPT test made by comparing antihydrogen and hydrogen is that it eventually will be more stringent than existing tests with leptons and baryons (Table 1). Here the accuracy of the CPT test must be distinguished from the accuracy with which the relevant physical quantity must be measured since these can be very different. The most accurate baryon CPT test is the $1 \times 10^{-9}$ (1 ppb) comparison of the charge-to-mass ratios of the antiproton and proton mentioned above [7]. For this measurement, as for the proposed antihydrogen/hydrogen comparison, the CPT test accuracy is the same as the measurement accuracy, requiring extremely accurate measurements. CPT tests with leptons and mesons involve free enhancement factors that make the accuracy of the CPT test to be substantially greater than the corresponding accuracy needed in a measured quantity. The most accurate lepton CPT test is a $2 \times 10^{-9}$ comparison of measured magnetic moment anomalies of electron and positron [8], interpreted as a comparison of magnetic moments at $2 \times 10^{-12}$. A single meson CPT test is even more precise [9]. The delicately balanced nature of the unique kaon system makes it possible to interpret a measurement at an accuracy of only $2\times10^{-3}$ as a comparison of the masses of the $K_0$ and $\bar{K}_0$ to an astounding $2\times10^{-18}$. (A theoretical speculation [3] suggests 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 the table and in Fig. 2.

Table 1: Comparing the CPT Tests

| | CPT Test Accuracy | Measurement Accuracy | Enhancement Factor |
|---|---|---|---|
| Mesons ($K_0\bar{K}_0$) | $2 \times 10^{-18}$ | $2 \times 10^{-3}$ | $10^{15}$ |
| Leptons ($e^+e^-$) | $2 \times 10^{-12}$ | $2 \times 10^{-9}$ | $10^3$ |
| Baryons ($p\bar{p}$) | $1 \times 10^{-9}$ | $1 \times 10^{-9}$ | 1 |
| (goal in 1996-97) | ($1 \times 10^{-10}$) | ($1 \times 10^{-10}$) | 1 |

In principle, the comparisons of antihydrogen and hydrogen could make possible a CPT test at the meson precision. The 1s-2s transition has an extremely narrow fractional linewidth of only $4\times10^{-16}$. With a measurement signal-to-noise ratio of 200, line splitting by this factor would allow a comparison at the kaon precision. There are serious obstacles to attaining this extremely high precision, including a 2.4 mK laser cooling limit, a second order Doppler shift, and possible Zeeman shifts depending on the configuration of the magnetic trap. Nonetheless, even a measurement at an accuracy of $10^{-13}$, the level at which the difficulties mentioned seem manageable in the first traps, would give a substantially improved CPT test involving leptons and baryons.

The most precise laser spectroscopy of hydrogen attained so far is illustrated in Fig. 3. It was obtained with a cold hydrogen beam by one group in this collaboration [10]. The narrowest observed width, 8.5 parts in $10^{13}$, is still much wider than the natural linewidth, but we expect that steady and substantial improvements in accuracy will continue as they have been 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 involving baryons and leptons. A use of cold trapped hydrogen for 1s-2s spectroscopy [11], in an environment similar in many respects to that which we hope to arrange for antihydrogen, comes very close to this linewidth.

The ratio of the 1s-2s transition frequencies can be used to determine a ratio of Rydberg

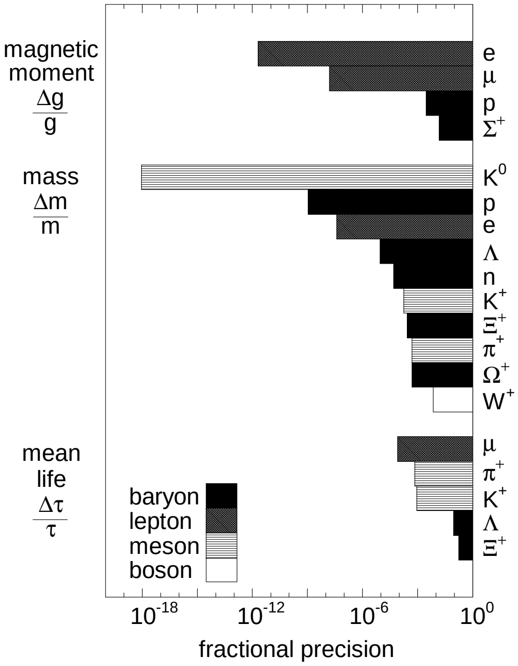

Figure 2: Tests of CPT Invariance. The particle-antiparticle pair is identified on the right. The shading indicates whether the comparison involves leptons, mesons or baryons. The accuracy achieved in the comparison is indicated below. Charge-to-mass ratio comparisons are included in "mass" measurements.

constants. It is instructive to express this ratio in terms of other fundamental constants

$$\frac{R_\infty(\bar{H})}{R_\infty(H)} = \frac{m[e^+]}{m[e^-]} \left(\frac{q[e^+]}{q[e^-]}\right)^2 \left(\frac{q[\bar{p}]}{q[p]}\right)^2 \frac{1 + m[e^+]/M[\bar{p}]}{1 + m[e^-]/M[p]}$$

(assuming the Coulomb interaction to have the same form for $\bar{H}$ and $H$). The only ratios on the right that have been measured accurately are the electron-to-proton mass ratio and the ratio of the electron and proton charges. This CPT test comparison thus clearly involves fundamental lepton and baryon constants but in a combination which makes it difficult to simply interpret the comparison as a measurement of the electron-to-positron mass ratio, or any other such simple ratio. The comparison of 1s-2s transition frequencies measured for antihydrogen and hydrogen would be a test of CPT invariance that involves the charges and masses of leptons and baryons at an unprecedented precision.

A second motivation for experiments which compare cold antihydrogen and hydrogen is the possibility to search for differences in the force of gravity upon antimatter and matter [12]. 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 ATRAP Collaboration have considered the possibility of gravitational measurements with trapped antihydrogen [13], and routinely time the free fall of cold atoms released from a trap [14]. We are intrigued by the possibility of experimental comparisons of the force of gravity upon antihydrogen and hydrogen, and will pursue this direction when the techniques are sufficiently advanced to permit attaining an interesting level of precision.

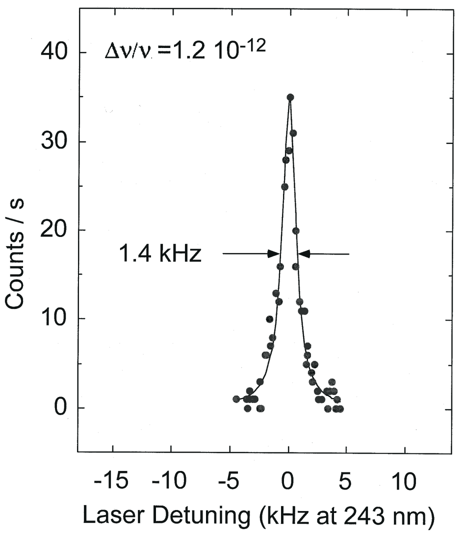

Figure 3: Narrow resonance line of the $1s - 2s$ $(F = 1)$ transition in hydrogen.

## 3. Great Progress and Excitement at the AD

Of course, no cold antihydrogen can be made and studied unless cooled low-energy antiprotons are available, and CERN is the unique source of such antiprotons. Through 1996, the only such antiprotons ever available came from the unique LEAR facility at CERN. Several years later, so that antihydrogen experiments could be carried out, CERN constructed the Antiproton Decelerator (AD). The AD delivers 100 MeV/c pulses that are less intense than those from LEAR but are available more frequently.

ATRAP grew out of the TRAP Collaboration (PS196) which developed the techniques to reduce the energy of antiprotons by more than a factor of $10^{10}$ below than the energy with which they were delivered by LEAR (and the AD). TRAP developed and first demonstrated the techniques whereby antiprotons from LEAR are now routinely slowed in matter, trapped [15], and then electron-cooled to 4 K [16, 17]. The surrounding vacuum was so good that antiprotons were stored for months at an energy $10^{10}$ times below the energy of antiprotons in LEAR [17]. These slowing, trapping and cooling methods form the basis of experiments by ATRAP, ATHENA (now ALPHA and AEGIS) and ASACUSA at the AD.

Great progress has been made at the AD towards the antihydrogen research goals laid out long ago by members of the TRAP Collaboration [18], and currently being pursued by ATRAP and ALPHA – cold antihydrogen stored in a magnetic trap for precise measurements [19]. Electrons and protons in a nested Penning trap were used to demonstrate that oppositely charged species, like antiprotons and positrons, could be made to interact with a very low relative velocity [20]. Before LEAR closed, modest numbers of cold positrons and cold antiprotons had already been stored together and made to interact [21]. The TRAP collaboration demonstrated that successive pulses of such antiprotons can be accumulated within a trap [16, 17, 22], thereby providing a much less expensive alternative to CERN's Antiproton Accumulator (AA). ATRAP, ATHENA and ALPHA all use this stacking technique.

We were gratified at the widespread excitement that arose when ATHENA [23] and ATRAP [24, 25] reported observations of slow antihydrogen, produced during the positron-cooling of antiprotons that ATRAP had developed and demonstrated earlier[26]. Such excitement had not been seen since nine antihydrogen atoms were originally observed at LEAR [27], despite the small number and extremely high energy that made it impossible to make any accurate measurements in this case. ATRAP then demonstrated a second method to produce cold antihydrogen, using lasers to control resonant charge exchange interactions [28, 29].

We anticipate that continued progress toward highly accurate laser spectroscopy of antihydrogen will continue to generate much interest within and beyond the scientific community.

## 4. Not the Usual CERN Experiment

The low-energy, high precision antihydrogen research differs substantially from the normal high energy particle and nuclear physics experiments that are practiced so successfully at CERN. Most CERN experiments are carefully crafted so that with a large number of particles delivered to an interaction region over some years, a signal of a particular interaction or particle will be established (or not) at a desired and predictable level of statistical accuracy.

Antihydrogen experiments, like most highly accurate low-energy experiments, are very different. Most of the experimental time is spent in inventing new techniques and methods that make it possible to see a signal at all. A long sequence of short experiments require very precise control and preparation, but the result of one short experiment helps decide what short experiments will follow it. Longer term time schedules are thus less predictable than is normal for CERN high energy experiments. Once a signal is found, the accuracy attained is rarely statistical, being generally limited by systematic uncertainties.

Many other examples can be given for extremely precise measurements being realized after considerable time and effort. One is that the extremely accurate hydrogen spectroscopy experiments by an ATRAP collaborator who was recognized with the 2005 Nobel prize [30]. The recent electron magnetic moment measurement and the fine structure constant measurement made recently by another in our collaboration is another example [31].

In the past, some on the SPSC committee have had difficulty understanding the difference between the high energy experiments that they are involved in at CERN, and this low energy antihydrogen research program. They have wanted time lines which show clearly and precisely what accuracy antihydrogen spectroscopy will be attained with what number of antiprotons delivered from the AD. It is important to realize that we spend most of our time at ATRAP inventing and refining new methods which eventually should make it possible to see and use an antihydrogen spectroscopy signal.

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 the 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. Most of the TRAP time and effort went into developing, demonstrating and improving apparatus and techniques, rather than into accumulating statistics with a fixed apparatus. There was some risk insofar as much had yet to be invented, but after a decade of concentrated effort by a small team, the ambitious goal was met and even substantially exceeded.

# B. ATRAP Milestones

The milestones for the ATRAP antihydrogen research program are basically the same as when ATRAP made the initial proposal to the SPSC. What has changed, of course, is that substantial progress has been made, and more detailed strategies and methods are now clear in some cases. What has not changed, is that this is still the ambitious, long term research program that was approved by the SPSC.

1. **Develop methods for the robust stacking of antiprotons.** Although we had demonstrated the first antiproton stacking in a trap long ago, more extensive and robust extensions of the method are required if more than $2 \times 10^4$ antiprotons are to be used at one time for producing antihydrogen.
   **Status:** ATRAP did this initially for a small trap.
   **Reference:** ATRAP, Phys. Lett. B **548**, 140 (2002).

2. **Develop methods to fill a small trap with positrons.** We developed the first method to load large numbers of positrons into a cryogenic trap at high field.
   **Status:** Up to 5 million positrons were accumulated – enough to fill a small Penning trap to its useful limit. Great care was required to reuse the positrons during antiproton experiments.
   **Reference:** ATRAP Members, Phys. Rev. Lett. **84**, 859 (2000).
   **Reference:** ATRAP, Phys. Lett. B 507, 1 (2001).

3. **Develop methods to use positrons to cool antiprotons in a nested Penning trap,** a method and device that we proposed long ago for this purpose [18]. After earlier experiments [20] in which we used electrons to cool protons in a nested Penning trap [18], we demonstrated that this could also be done with positrons and antiprotons – as needed to make antiprotons and positrons interact at low relative velocities to produce slow antihydrogen.
   **Status:** Both ATRAP and ALPHA now use this technique to produce slow antihydrogen, using different methods to detect the antihydrogen.
   **Reference:** ATRAP, Phys. Lett. B 507, 1 (2001).

4. **Develop methods to produce antihydrogen during positron cooling of antiprotons.**
   **Status:** Both ATRAP and ALPHA now regularly use this method to produce antihydrogen.
   **Reference:** ATRAP, Phys. Rev. Lett. **89**, 213401 (2002).

5. **Develop a method to drive the production of cold antihydrogen.** This method provides a way to reuse antiprotons and positrons to produce more antihydrogen per antiproton and positron.
   **Reference:** ATRAP, Phys. Rev. Lett. **89**, 233401 (2002).

6. **Develop methods to measure the internal structure of antihydrogen atoms.** So far the ATRAP field ionization method is the only probe of the internal structure of antihydrogen atoms, showing that most or all of the antihydrogen atoms observed so far are in highly excited internal states.
   **Reference:** ATRAP, Phys. Rev. Lett. **89**, 213401 (2002).
   **Reference:** ATRAP, Phys. Rev. Lett. **89**, 233401 (2002).
   **Reference:** ATRAP member and others, Phys. Rev. Lett. **92**, 133402 (2004).

7. **Develop a method to measure the energy of the antihydrogen produced during the positron cooling of antiprotons.** Low velocity antihydrogen atoms must be produced if they are to be confined in a magnetic trap.
   **Status:** The observed antihydrogen has a measured energy that is higher than we had hoped, and we have not yet been able to demonstrate the lower energy antihydrogen that we think

that this method should be able to produce with careful tuning. A recent hypothesis suggests that this is due to charge exchange.
**Reference:** ATRAP, Phys. Rev. Lett. **93**, 73401 (2004).
**Reference:** ATRAP member and others, Phys. Rev. Lett. **97**, 143401 (2006).

8. **Develop methods to produce antihydrogen using a field-assisted formation method [32].**
   **Status:** We were not successful in realizing this method, in part because of the much larger production rate for antihydrogen from the three-body formation process.

9. **Develop a continuous source of Lyman $\alpha$ radiation with an intensity that suffices for laser cooling and 1s-2p spectroscopy.**
   **Status:** ATRAP members at Garching (now from Mainz and Amsterdam) developed the first such source, and demonstrated its usefulness for hydrogen spectroscopy.
   **Reference:** ATRAP Members, Phys. Rev. Lett. **83**, 3828 (1999).
   **Reference:** ATRAP Members, Phys. Rev. Lett. **86**, 5679 (2001).

10. **Develop methods to use lasers to control antihydrogen production via resonant charge exchange collisions.** We used this method to first produce cold Rydberg positronium at Harvard, and then to produce what could be the first truly cold antihydrogen atoms at the AD.
    **Reference:** ATRAP Members, Phys. Rev. A **57**, 1668 (1998).
    **Reference:** ATRAP, Phys. Lett. B **597** 257 (2004).
    **Reference:** ATRAP, Phys. Rev. Lett. **93**, 263401 (2004).

11. **Develop a method to measure the expected low energy of the antihydrogen atoms produced during the laser-controlled charge exchange process.**
    **Status:** Not possible so far; larger numbers of antihydrogen atoms are needed.

12. **Develop methods to deexcite the internal state of antihydrogen atoms produced during positron-cooling of antiprotons.** Ground state antihydrogen atoms are desired for the most accurate antihydrogen spectroscopy. The larger traps and larger numbers of particles that seem to be required are now available, so work on this can resume.

13. **Develop methods to reduce the kinetic energy of antihydrogen atoms produced during positron-cooling of antiprotons.**
    **Status:** It seems like the nested Penning trap should be capable of producing much lower energy antihydrogen atoms than have been observed so far. A variation on our method to produce antihydrogen during the positron-cooling of antiprotons seems very promising here. The demonstration of 1 K plasmas is a very important step towards this goal.

14. **Develop methods to deexcite the internal state of antihydrogen atoms produced during laser-controlled charge exchange collisions.** The larger positron plasmas now available should make it possible to collisionally deexcite antihydrogen atoms to lower excited states, so work can begin on this.

15. **Develop methods to reduce the kinetic energy of antihydrogen atoms produced during laser-controlled charge exchange collisions.**
    **Status:** More positrons are required to make more antihydrogen. These are now available, so this is one priority for the coming year. The demonstration of 1 K plasmas is a very important for this goal.

16. **Develop methods to produce ground state antihydrogen directly by using $CO_2$ lasers to stimulate the antihydrogen formation,** as we proposed long ago [18].
**Status:** This method was tried by ATHENA, but without success (so far).

17. **Develop laser methods to detect antihydrogen atoms in lower excited states than can be detected via field ionization.** We had time to just begin exploring this method, and we hope to return to it with larger numbers of cold antihydrogen atoms.

18. **Construct a much larger trap apparatus with room for magnetic traps and laser access.**
**Status:** A large superconducting solenoid is now in place at CERN. An entirely new trap apparatus was commissioned at the AD. All major parts are now working very well.

19. **Develop methods to introduce the much larger numbers of positrons needed to fill our larger Penning traps.** A different positron accumulation method is required to accumulate more than the 5 million positrons which filled our smaller traps.
**Status:** A substantial apparatus constructed at York University, of the same type developed at Bell Labs [33] (and used at ATHENA), has been commissioned at the AD. A positron guide now regularly transports positrons to the ATRAP II solenoid. We now routinely start an antihydrogen production experiment with 60 million positrons.

20. **Develop methods to image antiproton annihilation distributions in real time.**
Status: A three-layer, scintillating fiber detector for antiproton annihilations, constructed at the Juelich laboratory, was commissioned at the AD, but two layers were soon removed to make room for the addition of a Ioffe trap.

21. **Develop magnet traps and methods that prevent magnetic traps from causing the loss of accumulated positrons and antiprotons.** Long ago we suggested that antihydrogen spectroscopy would be best carried out in a magnetic trap [19], and both ATRAP and ALPHA are pursuing this goal, and many calculations have been preformed. The challenge is avoiding the loss of antiprotons and positrons before antihydrogen is made, and moving these particles into locations in which antihydrogen can be made, when a magnet trap is present.
**Status:** The stable confinement of antiprotons in a Penning-Ioffe trap was demonstrated.
**Reference:** ATRAP Members, Phys. Rev. Lett. **86** 5266 (2001).
**Reference:** ATRAP, Phys. Rev. Lett. **98** 113002 (2007).

22. **Produce and detect antihydrogen within a Penning-Ioffe trap.**
**Status:** The production of antihydrogen within a Pening-Ioffe trap was demonstrated, despite predictions of some competitors that this would not be possible. Two key innovations were developing methods to cope with poor cooling in a 1 Tesla magnetic field and making short plasmas.
**Reference:** ATRAP, Phys. Rev. Lett. **100**, 113001 (2008).

23. **Look for the antimatter counterparts of $H^-$ and $H_2^+$.** No one has ever looked for the production of these ions, even though they would be extremely cold antihydrogen atoms could be produced by ionizing or dissociating these species, respectively.
**Status:** We have demonstrated the detection sensitivity required to see one ion.

24. **Develop methods to measure the magnetic moment of a single trapped antiproton.** If the spin flip of an antiproton can be detected nondestructively (a very challenging undertaking), then it should be possible to measure the magnetic moment of an antiproton more than a million times more accurately. We have discussed this exciting possibility with

the SPSC on several occasions, including the way that it would be done as a parasitic experiment at ATRAP.
**Status:** Apparatus to demonstrate the non-destructive detection of a proton spin flip has been built at Harvard and at Mainz. A single trapped proton is being studied at Harvard.
**Reference:** ATRAP Members, Phys. Rev. Lett. **94**, 113002 (2005).

25. **Develop methods to confine antihydrogen atoms in a magnetic trap, and demonstrate that antihydrogen atoms have been trapped.**
**Status:** We detected no trapped antihydrogen atoms this year, being limited by our detection sensitivity and background, cut short by the cancelation of the AD beam extension. We hope to return to this in 2009-2010, and anticipate the delivery of a new Ioffe trap that can be turned off more rapidly.

26. **Develop methods to deexcite trapped antihydrogen atoms.** Now that we have much larger positron plasmas to allow more collisional deexcitation we can turn our attention to this important issue.

27. **Make a new version of the Lyman alpha source that has more power, and is also compact and robust enough to use at the CERN AD.**
**Status:** Substantial performance gains in the 254 nm and 545 nm laser systems needed for the continuous Ly $\alpha$ source were realized this year at Mainz, including the first Lyman $\alpha$ produced by the new system. It is anticipated that a greatly improved source should be demonstrated during this year.
**Reference:** ATRAP Members, Optics Lett. **32**, 955-957 (2007).
**Reference:** ATRAP Members, Optics Express **15**, 14476 (2007)).

28. **Observe 1s-2p transitions of antihydrogen using the continuous, coherent Lyman alpha radiation source.**

29. **Develop and demonstrate methods to use the coherent source of Lyman alpha radiation to cool trapped antihydrogen atoms.**

30. **Develop methods to perform off-resonant two-photon spectroscopy of antihydrogen.** This offers a higher accuracy than 1s-2p spectroscopy, with a larger signal than does 1s-2s spectroscopy.

31. **Observe 1s-2s transitions in antihydrogen.** This transition offers the highest possible resolution, for comparisons of antihydrogen and hydrogen.

32. **Study the systemic errors introduced for the spectroscopy of antihydrogen in the confined space of an accelerator hall.** Measurements of this high accuracy are almost always limited by how systematic errors are managed, rather than by statistics. Possible sources of such errors must be painstakingly investigated one at a time.

33. **Make a series of measurements of the 1s-2s transition frequency with increasing accuracy.** This is the ultimate goal of the antihydrogen spectroscopy. The precision of such measurements with hydrogen has been slowly improving for many years. Antihydrogen spectroscopy will be done with many fewer atoms.

34. **Study the gravitational acceleration of antihydrogen.** We will be seeking to produce antihydrogen atoms that are cold enough that we can probe the gravitational acceleration of antihydrogen atoms.

# C. Looking Back at 2009 and Forward to the 2010 Antiproton Run

The 2009 antiproton run was a good one on the accelerator side and on the ATRAP side, given the extension that was granted. Our focus was searching for trapped antihydrogen atoms that are produced from larger numbers of colder positrons and antiprotons.

## 1. Many More Slow Antiprotons Become Available

The use of a Ioffe trap required that we lower the magnetic field in our Penning trap to 1 Tesla. The number of antiprotons that we captured per shot from the AD went down substantially as we reduced the field from 3 to 1 Tesla.

Anticipating this we had an additional solenoid constructed which would boost the magnetic field in the capture region of our trap. We used this solenoid first during the 2008 beam run. It worked extremely well, substantially boosting the number of cooled antiprotons that could be accumulated per AD shot. However, we experienced substantial losses as the magnetic field changed from 3 Tesla to 1 Tesla.

During the 2009 run we spent a substantial time identifying and reducing these losses. Eventually, we were able to essentially eliminate these losses. As the beam run closed we were in the process of speeding up the process. We antipate further progress in 2010.

We are now able to robustly accumulate up to 5 million antiprotons per hour for antihydrogen production trials. The much larger numbers of antiprotons are crucial to our plans to produced a usable number of cold antihydrogen atoms using our laser-controlled charge exchange method. Well over an order of magnitude more antiprotons are now available compared to what was used previously.

## 2. Plasma Temperatures Lowered to 1.2 K

For the first time ever, very large 1.2 Kelvin plasmas of trapped electrons and positrons were produced. They were also used to produce antihydrogen atoms. The lowest temperatures realized before at the AD were 4 K - 10 K. Early in 2008 we installed a cryogenic system designed to lower the temperature of our trap electrodes to 1.2 K. The new system worked very well. We measured 1.2 K electrode temperatures at both ends of the very long stack of our cylindrical trap electrodes.

Electron and positron plasmas cool efficiently by the spontaneous emission of synchrotron radiation until they are in thermal equilibrium with the surrounding trap electrodes. We were able to measure the change in temperature of an electron plasma, demonstrating that it tracked the temperature change of the surrounding trap electrodes at the 1 Kelvin level.

The lower temperature is potentially extremely important for trapping antihydrogen atoms. The depth of a good magnetic trap is only about a half Kelvin deep. Antihydrogen atoms that are made from plasmas that are 4 to 10 K by proven techniques cannot be colder than these temperatures. This means that very few of the produced antihydrogen atoms can possibly have an energy that is low enough for them to be trapped. The situation changes dramatically going from 4 - 10 K down to 1 Kelvin. If a thermal distribution of antihydrogen atoms is produced, for example, the lower temperature goes into the exponent of a Boltzmann distribution for the energies of the antihydrogen atoms. The potential number of antihydrogen atoms cold enough to be trapped is thus much larger if this temperature is 1.2 Kelvin rather that 4 - 10 Kelvin.

On the long term we would thus like to use methods developed and demonstrated at Harvard to use a dilution refrigerator to lower the plasma temperature to 100 mK but this difficult challenge will take a lot of time and resources.

During 2009 we concentrated on improving our detection sensitivity to decrease the time needed to measure the temperature of electron and positron plasmas. We were able to incorporate these plasmas diagnostics so that they could be used for every plasmas prepared for an antihydrogen production trial.

We verified that we could again observe plasmas that seem to be at 1.2 K. This was very gratifying. However, we were also able to produce plasmas that we measure to have temperature higher by a factor of 4 or 5. We have not yet published the exciting low temperature results because we are still in the process of understanding better the circumstances under which the lowest temperatures can be realized.

## 3. Observing Single Antiprotons

We have long wished to see if either the antimatter counterpart of the negative hydrogen atom, or the antimatter counterpart of the hydrogen molecular ion, is produced when antiprotons and positron interact within a nested Penning trap.

Long ago at LEAR we observed the production of negative hydrogen ions and used these to make what is still the best test of CPT invariance with a baryons/antibaryon system. In smaller traps than we currently use (not optimized for antihydrogen production) we were able to observe a single trapped antiproton and a single trapped negative hydrogen ion with great signal-to-noise. Since large numbers of antimatter ions are almost certainly not produced, a search for antimatter ions would required a sensitivity to small number of ions. The first challenge of a search for antimatter ions is to see if we could achieve one-ion sensitivity in a larger trap designed for antihydrogen production.

We installed a first version of detection amplifiers designed to detect single and cool ions. These were used to detect and cool antiprotons. We were excited to eventually detect and distinguish individual antiprotons by resolving the cyclotron frequencies of antiprotons that were excited to very different cyclotron energies. We typically did these studies by keeping the last antiprotons that we captured in our trap at the end of a beam shift, and investigating these during following shifts while no additional antiprotons were available to us.

We encountered one unexpected challenge. When we ramped the Ioffe trap up and down during the shift we found a substantial change in the magnetic gradient; this changed our ability to resolve small numbers of ions. This requires more investigation but the complication will likely not limit our search in the long term.

We were planning to make an initial search for anti-$H^-$ ions during the last month of the antiproton beam run but were unable to carry out this plan since the end of the AD run was canceled. We hoped to pursue this in 2009. However, we did not manage to get to these studies. Given the ambitious agenda we have for 2010 it is not clear that we will have time to go back to this interesting program yet in 2010, but we will if we can fit it in.

## 4. Controlled Ioffe Trap Quenches

During the 2007 run we quenched our Ioffe trap after producing antihydrogen within our Ioffe trap since this was the fastest way to release trapped atoms for the most efficient detection. Although this worked well enough for us to set a limit on the number of trapped atoms, we could not accumulate good statistics given the difficulty triggering the quenches in a predictable and controllable way. For the 2008 run we installed a heater that could deliver a pulse of heat to the Ioffe trap. This worked very well, allowing us to trigger quenches with a greatly improved reproducibility, on the time scale of a second or two. We were thus poised to make a concerted effort to search for trapped antihydrogen atoms just at the AD run was truncated a month earlier than we expected. We returned to searching for trapped antihydrogen atoms during 2009, with much larger numbers of antiprotons per trial than has ever been possible before. That we have not yet observed trapped antihydrogen atoms confirms our suspicions that we need colder atoms, which helps motivate our focus upon lower temperature plasmas of positrons, and using colder electrons to make colder antiprotons.

## 5. Lyman Alpha Laser System

A continuous Lyman alpha laser system is needed for cooling trapped antihydrogen atoms and for initial spectroscopy experiments. The first continuous Lyman alpha system was demonstrated by ATRAP members several years ago.

Recent efforts have focused upon making a much more intense Lyman alpha source that is also much more robust, as is desirable for operation at an accelerator facility. A new solid state laser system has been constructed, and during 2008 it produced its first Lyman alpha radiation. The first intensity was not high, and there has been some (recently remedied) trouble with a disk laser. During 2009 the focus was upon increasing the radiation intensity.

Lyman alpha laser access to our trap is available in our ATRAP apparatus. Our first generation Ioffe trap, and the second generation trap that is under construction, both have Lyman alpha access along and perpendicular to the trap axis.

## 6. Antihydrogen by Charge Exchange

We worked hard to duplicate and improve upon the antihydrogen production via the Cs charge exchange method that ATRAP demonstrated several years ago in a much smaller trap with many fewer trapped particles used to form the antihydrogen. The crucial first step, summarized above, is in producing much larger number of antiprotons than were available for the earlier experiments. Many more positrons were already available.

For producing antihydrogen by Cs charge exchange we developed a new diode-based green laser system and buildup cavity to excite Cs atoms up to a Rydberg state. This replaces the pulsed laser system that we used in the past. It is tunable and has a much narrower bandwidth. The improved laser systems worked very well.

We succeeded in sending Rydberg Cs atoms through that larger trap and detected in on the other side of the trap. However, we encountered two difficulties. First, more Cs atoms were required for the year's operation than could be stored in our Cs sources. We are now testing a higher capacity source that recently became available in the hope of incorporating such a source for 2010. Second, we found that the Rydberg Cs atoms passing through the trap heated antiprotons trapped nearby. This heating mechanism was not a problem in our smaller traps with fewer trapped antiprotons, and it remains to be understood.

## 7. Second Generation Ioffe Trap

We earlier reported that a second generation Ioffe trap was under construction. Delivery had been promised in time for us to get the new trap into the antiproton beam in 2008. However, this schedule slipped significantly. The news got worse before it got better. The production company was unable to demonstrate prototype milestones that were part of the production process, and they then backed out of the contract. We got back on track by solving some of the technical problems ourselves, and agreeing to take on a substantial part of the necessary fabrication.

During 2009 the second generation Ioffe trap was actually constructed. Half of the winding have been successfully tested. The promised delivery by the end of 2009 did not happen, but we are expecting delivery in the next couple weeks, depending upon the final testing schedule now being discussed.

Incorporating the completed coils into a vacuum enclosure with laser access windows is a very tricky procedure. We fervently hope that we will be able to carry this out in February or March, and then install this into a third ”CTRAP” apparatus. However, we expect to start the 2010 beam run using the ”BTRAP” apparatus used during 2009, but with a better Cs source installed.

### 8. Second Refrigerator-Cooled Dewar

During 2009 it took about a minimum of two weeks to warm up the BTRAP apparatus, remove it from the the superconducting solenoid, make a modification, reinstall the apparatus in the solenoid, and cool it back to 1.2 K. A copy of the refrigerator-cooled dewar that cools the BTRAP apparatus is undergoing its final trials this week. This apparatus should make it possible for us to precool the CTRAP apparatus before removing the BTRAP apparatus. We hope that the time constant for switching from one apparatus to the other will be days rather than weeks.

### 9. New ATRAP Platform

A new ATRAP platform was designed and constructed to give us badly needed room for new equipment and for helium and nitrogen dewars. This platform gives us room for the apparatus additions that we continue to make in the limited area of our elevated platform. The platform works very well, allowing us to use liquid helium, a resource sometimes in short supply at the AD, with less transfer loss. This year we need to bring more electrical power to this platform. Unfortunately, this is extremely expensive.

## D. We Cannot Succeed Without Antiprotons

The SPSC has expanded the number of teams pursuing cold antihydrogen from 3 to 4. We have no objection to this in principle. The antiprotons should go to whatever teams, old or new, who can put them to the best use. However, the SPSC should note that the number of antiprotons is what now limits how rapidly antihydrogen progress can be made. Adding an additional team that shares the limited number of available antiprotons will slow progress for all. We now hope that the SPSC and CERN will vigorously pursue an increase in the number of antiprotons available at the AD.

## E. The ELENA Advantage

The small storage ring sometimes called “ELENA” would offer an important advantage for antihydrogen research. The size of the advantage is easy to estimate. In ATRAP experiments, we capture and cool only a small fraction of the AD antiprotons. With the additional ELENA deceleration, we should be able to trap up to 100 times more antiprotons per AD pulse. Positrons would still greatly outnumber antiprotons in the large Penning traps, however, with the result that the behavior of the antiprotons should not change very much, and the antihydrogen production should simply scale up in proportion.

If it were available now, ELENA would provide a dramatic increase in the data taking rate for the ATRAP experiments. Much lower uncertainties would be acquired with the antiprotons accumulated in one pulse from the AD, than can be attained in a one hour accumulation of antiprotons under current AD operating conditions. For the future, this would translate directly into greatly improved signal-to-noise ratio for antihydrogen spectroscopy. The much larger antiproton number would have a hugely positive effect upon the ATRAP antihydrogen experiments.

We thank the SPSC for its strong support for the ELENA upgrade, and we request that this strong support continue. We hope that a way will be found to overcome the serious financial challenges in funding ELENA because it would be a tremendous upgrade to the AD.

We commend those who found a clever way to incorporate ELENA into the AD hall without the need to relocate the experiments or the AD. ELENA would provide a spectacular way for CERN to leverage its unique antiproton facility so that more and better experiments could be carried out.

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