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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. Recent Relevant Publications by ATRAP and its Members

1. "Antihydrogen Production in a Penning-Ioffe Trap"
   G. Gabrielse, P. Larochelle, D. Le Sage, B. Levitt, W. S. Kolthammer, R. McConnell, P. Richerme, J. Wrubel, A. Speck, M. C. George and D. Grzonka, W. Oelert, T. Sefzick, Z. Zhang, A. Carew, D. Comeau, E. A. Hessels, C. H. Storry, M. Weel, and J. Walz
   Phys. Rev. Lett. **100**, 113001 (2008).

2. "Antiproton Stability in a Penning-Ioffe Trap for Antihydrogen"
   G. Gabrielse, P. Larochelle, D. Le Sage, B. Levitt, W.S. Kolthammer, I. Kuljanishvili, R. McConnell, J. Wrubel, F.M. Esser, H. Glückler, D. Grzonka, G. Hansen, S. Martin, W. Oelert, J. Schillings, M. Schmitt, T. Sefzick, H. Soltner, Z. Zhang, D. Comeau, M. C. George, E.A. Hessels, C.H. Storry, M. Weel, A. Speck, F. Nillius, J. Walz, T.W. Hänsch
   Phys. Rev. Lett. **98**, 113002 (2007).

3. "Density and Geometry of Single Component Plasmas"
   A. Speck, G. Gabrielse, P. Larochelle, D. Le Sage, B. Levitt, W.S. Kolthammer, R. McConnell, J. Wrubel, D. Grzonka, W. Oelert, T. Sefzick, Z. Zhang, D. Comeau, M.C. George, E.A. Hessels, C.H. Storry, M. Weel, J. Walz
   Phys. Lett. B **650**, 119 - 123 (2007).

4. "Single Component Plasma of Photoelectrons"
   B. Levitt, G. Gabrielse, P. Larochelle, D. Le Sage, W. S. Kolthammer, R. McConnell, J. Wrubel, A. Speck, D. Grzonka, W. Oelert, T. Sefzick, Z. Zhang, D. Comeau, M.C. George, E .A. Hessels, C.H. Storry, M. Weel, and J. Walz
   Phys. Lett. B **656**, 25 (2007).

5. "750 mW Continuous-Wave Solid-State Deep Ultraviolet Laser Source at the 253.7 nm Transition in Mercury"
   M. Scheid, F. Markert, J. Walz, J. Wang, M. Kirchner, and T.W. Haensch,
   Optics Letters **32**, 955-957 (2007).

6. "4 W Continous-Wave Narrow-Linewidth Tunable Solid-State Laser Source at 546 nm by Externally Frequency Doubling a Ytterbium-Doped Single-Mode Fiber laser System"
   F. Markert, M. Scheid, D. Kolbe, and J. Walz,
   Optics Express **15**, 14476 (2007).

   Papers based upon the 2008 run are in progress.

B. 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 that makes this possible.

The motivations (p. 5) and milestones (p. 10) 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.

To mitigate the serious disruption to the antihydrogen research caused by the need to shut down CERN for one year during 2005, we used the year to build an ambitious new apparatus, which we refer to as ATRAP II. The ATRAP II apparatus, pictured and discussed in the original ATRAP proposal to the SPSC, takes advantage of what has been learned during antihydrogen experiments to date. To provide laser access, make room for magnetic traps, and allow the use of much larger positron plasmas, the apparatus is much larger than the earlier ATRAP I apparatus. A new positron source has been constructed to fill the larger traps with positrons in an efficient way. The ATRAP II apparatus is assembled in the second port of the ATRAP beam line — an experimental location that was built when the AD was constructed just for this purpose. The substantial weight of the positron accumulator is supported by the AD ring and a nearby pillar.

Commissioning of the ATRAP II apparatus began in 2006. In 2006, we elected to rearrange our priorities, to investigate the effect of a quadrupole Ioffe magnetic field (one way to trap antihydrogen atoms) upon antiprotons, the crucial question being whether the antiprotons would remain stored long enough so that antihydrogen could be produced. Our encouraging positive answer to this question was reported in Physical Review Letters [1].

The ATRAP II apparatus was brought into full operation during 2007. The final commissioning of the positron accumulator, delayed as part of the shift in priorities in 2006, was finished in 2007. We continue to work on optimizing the positron production and transfer efficiency in parallel with antihydrogen studies – during shifts when antiprotons are not available, and using accumulated positrons that are not needed for antihydrogen production.

In early 2008 we reported the first production of antihydrogen atoms within a Penning-Ioffe trap [2] - a very important milestone. The rest of 2008 did not go the way that we planned – a mixture of significant steps forward and some disappointments.

- We lowered the temperature of our electron and positron plasmas from 7 K (in 2007) to 1.1 K – a very significant advance we believe towards increasing the production of antihydrogen atoms that are cold enough to trap.
- We succeeded in observing single antiprotons in our trap, demonstrating the detection sensitivity needed to search for antihydrogen ion production.
- We succeeded in triggering reproducible quenches of our Ioffe trap to improve our detection sensitivity for trapped antihydrogen.
- We also had success with our laser systems, demonstrating an improved green laser system for Cs charge exchange production of antihydrogen, and the first Lyman alpha production with a solid state laser system.

However, beam quality difficulties early in the AD run hampered our progress before we had our week off. Our apparatus switch suffered from a repeated and time consuming component failure in the heart of our apparatus. And when this was finally under control, and our apparatus was all tuned to make progress, the LHC magnetic problem eliminated the last month of the AD run.

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].

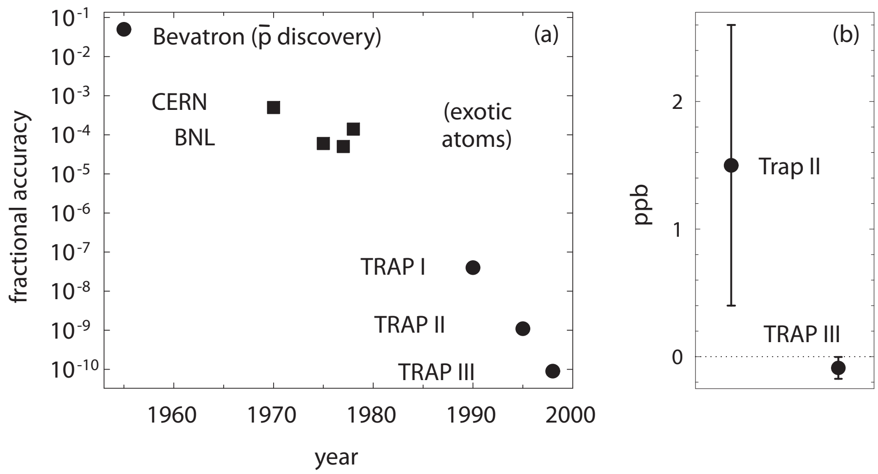

Figure 1: The accuracy at which antiprotons and protons have been compared [6].

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 1×10^{-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 2×10^{-9} comparison of measured magnetic moment anomalies of electron and positron [8], interpreted as a comparison of magnetic moments at 2×10^{-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 2×10^{-3} as a comparison of the masses of the K_0 and $\bar{K}_0$ to an astounding 2×10^{-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.

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 4×10^{-16}. With a measurement signal-to-noise ratio of 200, line splitting by this factor would allow

Table 1: Comparing the CPT Tests

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

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 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 re-

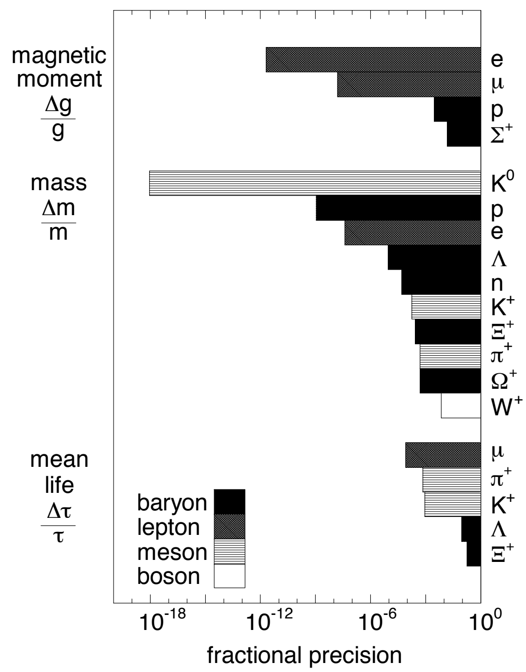

Figure 2: Tests of CPT Invariance. The particle-antiparticle pair is identified on the right. The shading indicates whether the comparison involves leptons, mesons or baryons. The accuracy achieved in the comparison is indicated below. Charge-to-mass ratio comparisons are included in "mass" measurements.

leased 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.

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

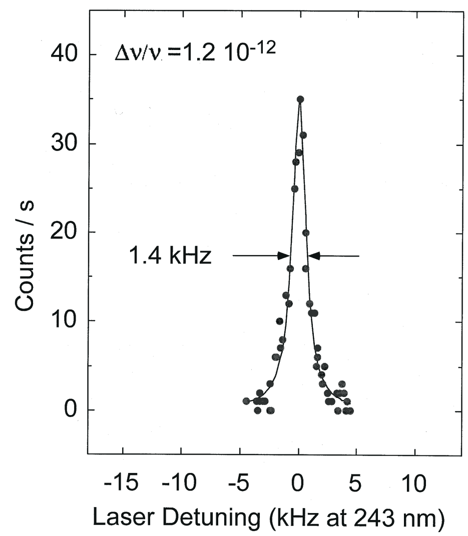

Figure 3: Narrow resonance line of the $1s - 2s$ $(F = 1)$ transition in hydrogen.

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.

C. 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 2×10^4 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 α 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 α source were realized this year at Mainz, including the first Lyman α 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.

D. Looking Back at 2008 and Forward to the 2009 Antiproton Run

The stability and intensity of the AD beam was not ideal in the first part of the 2008 antiproton run. We had difficulty making much progress. To compensate, CERN decided to extend the AD run into December – a reasonable plan that unfortunately was canceled just before the extension happened because of unfortunate developments at the LHC.

During a week without antiproton beam we began our planned apparatus exchange. Unfortunately, a titanium edge-welded bellows buried within our apparatus failed as we were about to cool this apparatus to take antiprotons. Since this bellows was operated with a very large safety margin compared to the manufacturers performance guarantee, our apparatus was not constructed to make for an easy bellows replacement. Much of the apparatus had to be removed before we could get access to replace the bellows and, after the replacement, much of the apparatus thus had to be built up again. When we finally were about to cool the apparatus to take antiprotons, the replacement bellows failed. It was a very difficult time for our exhausted team. Representatives of the bellows company made a site visit to CERN to figure out what we were doing wrong. Their conclusion was that we were doing nothing wrong, and their bellows were not performing as promised. We rebuilt the apparatus a second time and this time the bellows held. Bellows from other companies are being produced for our use in 2009. The apparatus is also being modified to make it much easier to replace a bellows if another fails.

There is no doubt that our component failure and the cancelation of the last month of the AD run seriously limited our productivity for 2008. Still, there was much progress to be pleased with in 2008. We have high expectations, as a result, for 2009.

1. Five Times More Antiprotons Available at 1 Tesla

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. This solenoid was available last year in time to incorporate it into the ATRAP apparatus at the end of the previous year's antiproton run. However, we were making such good progress, ending in our demonstration that antihydrogen could be produced within a quadrupole Ioffe trap, that we chose not to interrupt our progress to do the installation.

For the 2008 run we installed the catching solenoid. It worked extremely well, boosting the number of cooled antiprotons per AD shot by about a factor of five – a very significant improvement.

2. Plasma Temperatures Lowered to 1.1 K

For the first time ever, very large 1.1 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 1.1 K. The new system worked very well. We measured 1.1 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. Our long term goal is to trap 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 1.1 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.

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 sensitivity to small numbers 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 hope to pursue this in 2009.

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 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 intend to return to this during 2009.

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, but now that there is a signal to optimize considerable progress is expected during 2009.

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 had hoped to investigate antihydrogen production via the Cs charge exchange method that ATRAP demonstrated several years ago. Much larger plasmas of positrons are now available in our apparatus, so the number of antihydrogen atoms produced by this method should be significantly increased.

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. We also have incorporated a new and improved Cs source.

The apparatus was tested *in situ* last year and is now being slightly modified with the intention of using it to produce antihydrogen within the Penning-Ioffe trap in 2009.

7. Second Generation Ioffe Trap

Last year we reported that a second generation Ioffe trap was under construction by a company. Delivery had been promised in time for us to get the new trap into the antiproton beam in 2008, but we pointed out that the schedule had slipped significantly.

The news got worse before it got better. The 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 necessary fabrication.

Successful prototypes have now been completed, and the new trap is now truly under construction. We are trying hard to pursue a schedule that will allow us to use the new trap before the end of the year. However, this schedule cannot be guaranteed considering the history and considerable challenges of this project.

8. 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. The design of this platform was examined and approved by the appropriate parties at CERN, and is scheduled to be installed this week. This platform gives us room for the apparatus additions that we continue to make in the limited area of our elevated platform. It will allow us also to use liquid helium, a resource sometimes in short supply at the AD, with less transfer loss.

E. 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.

F. Optimal Use of Antiprotons

We have been offered the options of using antiprotons in 8 or 12 hour shifts. Given these two options, ATRAP prefers the 12 hour option for 2009. Given that we hope to spend part of the year commissioning our second generation Ioffe trap we will use the off weeks to make major apparatus changes.

For many years we have noted that we could make much more efficient use of antiprotons if we could move to a mode where we get antiprotons for a half hour and then switch them to another experiment for the next hour and a half. (Exact time periods could be negotiated.) We again encourage other users to consider this possibility, the time scale being dictated by the cooling times required for trapped particles in a 1 Tesla field. At the end of the antiproton run, the reproducibility of the beam line settings was good enough to allow switching users within a few AD cycles. We encourage the AD team to improve the rapid switching of the antiproton beam from one experiment as a high priority.

G. 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 – between 2×10^4 and 8×10^4 antiprotons from a pulse of 3×10^7 antiprotons.

With the additional ELENA deceleration, we should be able to trap and cool ten to fifty 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 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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