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The Production and Study of Cold Antihydrogen

by the Antihydrogen TRAP Collaboration (ATRAP)

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Contents

A. Relevant Publications by ATRAP and its Members

1 . "The Ingredients of Cold Antihydrogen: Simultaneous Confinement of Antiprotons and Positrons at 4 K"
G. Gabrielse, D.S. Hall, T. Roach, P. Yesley, A. Khabbaz, J. Estrada, C. Heimann, and H. Kalinowsky
Phys. Lett. B *455*, 311 (1999).

2. "Continuous Wave Coherent Lyman-alpha Radiation",
K.S.E. Eikema, J. Walz and T.W. Hänsch
Phys. Rev. Lett. *83*, 3828 (1999).

3. "Field Ionization of Strongly Magnetized Rydberg Positronium: A New Physical Mechanism for Positron Accumulation"
J. Estrada, T. Roach, J.N. Tan, P. Yesley, and G. Gabrielse,
Phys. Rev. Lett. *84*, 859 (2000).

4. "Comparing the Antiproton and Proton, and Opening the Way to Cold Antihydrogen",
G. Gabrielse,
In *Advances in Atomic, Molecular, and Optical Physics*, vol. 45, edited by B. Bederson and H. Walther, Academic Press, New York, pp. 1-39 (2001).

5. "Stability of a Combined Penning-Ioffe Trap",
T.M. Squires, P. Yesley and G. Gabrielse,
Phys. Rev. Lett. *86*, 5266 (2001).

6. "Continuous Wave Coherent Lyman-α Excitation of Atomic Hydrogen",
K.S.E. Eikema, J. Walz and T.W. Hänsch
Phys. Rev. Lett. *86*, 5679 (2001).

7. "First Positron Cooling of Antiprotons",
G. Gabrielse, J. Estrada, J. Tan, P. Yesley, N. Bowden, P. Oxley, C. Storry, M. Wessels, W. Oelert, G. Scheppers, D. Grzonka, T. Sefsick, H. Fermann, H. Zmeskal, W. Breunlich, H. Kalinowsky, and C. Wesdorp,
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8. "Stacking of Cold Antiprotons",
G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch, E.A. Hessels
Phys. Lett. B *548*, 140 (2002).

9. "Background-Free Observation of Cold Antihydrogen and a Field-Ionization Analysis of Its States",
G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch, E.A. Hessels
Phys. Rev. Lett. *89*, 213401 (2002).

10. "Driven Production of Cold Antihydrogen and the First Measured Distribution of Antihydrogen States",
G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch, E.A. Hessels
Phys. Rev. Lett. *89*, 233401 (2002).

11. "Strongly Magnetized Antihydrogen and Its Field Ionization",
D. Vrinceanu, B.E. Granger, R. Parrott, H. R. Sadeghpour, L. Cederbaum, A. Mody, J. N. Tan and G. Gabrielse
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12. "G. Gabrielse, et al. reply" (A reply to a Comment discusses comparing our measured field ionization spectra to theory)
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13. "Aperture Method to Determine the Density and Geometry of Anti-Particle Plasmas",
P. Oxley, N. S.Bowden, R. Parrott, A. Speck, C. Storry, J.N. Tan, M. Wessels, G. Gabrielse, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch and E. A. Hessels
Phys. Lett. B *595*, 60 (2004).

14. "First Measurement of the Velocity of Slow Antihydrogen Atoms",
G. Gabrielse, A. Speck and C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
Phys. Rev. Lett. *93*, 073401 (2004).

15. "Laser-Controlled Production of Rydberg Positronium",
A. Speck, C.H. Storry, E. Hessels and G. Gabrielse
Phys. Lett. B *597*, 257 (2004).

16. "First Laser-Controlled Antihdyrogen Production",
C.H. Storry, A. Speck, D. Le Sage, N. Guise, G. Gabrielse, D. Grozonka, W. Oelert, G. Scheppers, T. Sefzick, J. Walz, H. Pittner, M. Herrmann, T.W. Haensch, E.A. Hessels and D. Comeau
Phys. Rev. Lett. *93*, 263401 (2004).

17. "Atoms Made Entirely of Antimatter: Two Methods Produce Slow Antihydrogen" (Review Paper)
G. Gabrielse
Adv. At. Mol. Opt. Phys. *50*, 155-217 (2005).

18. "Single-Particle Self-excited Oscillator (includes application to measuring antiproton spin flips)
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B. Overview

1. Introduction

The ATRAP Collaboration is enthusiastic about returning to CERN to continue their antihydrogen research program at CERN's Antiproton Decelerator (AD). We are privileged to work at the unique AD facility – the only place in the world with the capability of producing the 5 MeV antiprotons needed for antihydrogen experiments.

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 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 proposed by the need to shut down CERN for one year, we used this year to build an ambitious new apparatus, which we will 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 and make room for magnetic traps, the apparatus is much larger than the ATRAP I apparatus. A new positron source will make it possible to fill the larger traps with positrons in an efficient way. The ATRAP II apparatus is being 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.

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 are thus now beginning to appear in the context of string theory [1, 2].

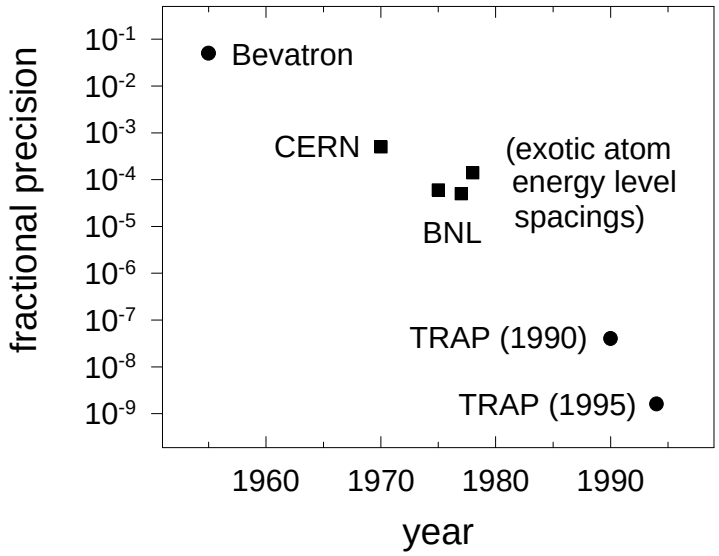

Figure 1: The accuracy at which antiprotons and protons have been compared.

Physics is an experimental science, however, and whether CPT invariance is exactly conserved is thus primarily 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 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 [3]. 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 [4], interpreted as a comparison of magnetic moments at 2×10^{-12}. A single meson CPT test is even more precise [5]. 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 [1] 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 ($K_0\bar{K}_0$)	2×10^{-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

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 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 [6]. 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. The recent first use of cold trapped hydrogen for 1s-2s spectroscopy [7], in an environment similar in many respects to that we hope to arrange for antihydrogen, comes very close to this linewidth, with very large improvements expected when laser jitter is reduced.

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

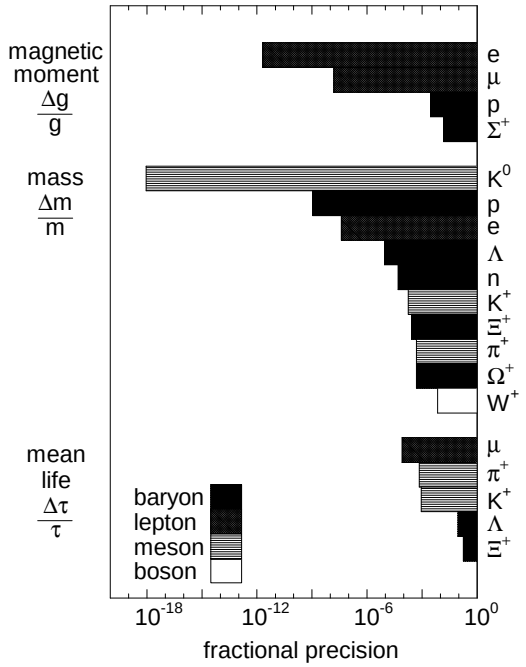

Figure 2: Tests of CPT Invariance. The particle-antiparticle pair is identified on the right. The shading indicates whether the comparison involves leptons, mesons or baryons. The accuracy achieved in the comparison is indicated below. Charge-to-mass ratio comparisons are included in "mass" measurements.

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 [8]. 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 [9], and routinely time the free fall of cold atoms released from a trap [10]. 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.

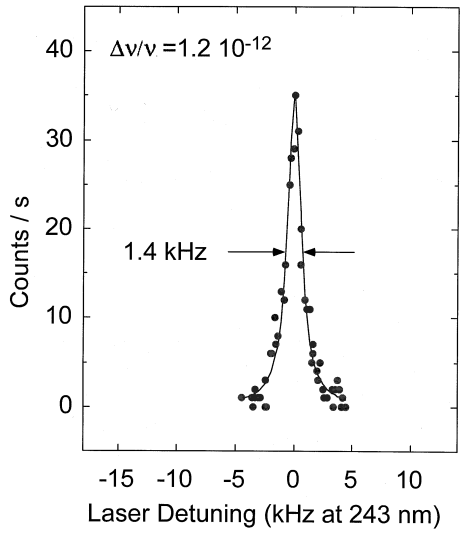

Figure 3: Narrow resonance line of the $1s - 2s$ ($F = 1$) transition in hydrogen.

3. Great Progress and Excitement at the AD

Of course, no cold antihydrogen can be made and studied unless cooled MeV 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.

Antiprotons with an energy more than 10^{10} times lower than what was produced by LEAR and the AD, were developed at CERN by the TRAP Collaboration (PS196), from which ATRAP grew. TRAP developed and first demonstrated the techniques whereby antiprotons from LEAR are now routinely slowed in matter, trapped [11], and then electron-cooled to 4 K [12, 13]. 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 [13]. These slowing, trapping and cooling methods form the basis of experiments by ATRAP, ATHENA and ASACUSA at the AD.

Great progress has been made at the AD towards antihydrogen research goals laid out long ago by members of the TRAP Collaboration [14], and currently being pursued by ATRAP and ATHENA – cold antihydrogen stored in a magnetic trap for precise measurements [15]. Electrons and protons in a nested Penning trap were used to demonstrate that oppositely charge species, like antiprotons and positrons, could be made to interact with a very low relative velocity [16]. Before LEAR closed, modest numbers of cold positrons and cold antiprotons have already been stored together and made to interact [17]. The TRAP collaboration has demonstrated that successive pulses of such antiprotons can be accumulated within a trap [12, 13, 18], thereby providing a much less expensive alternative to CERN's Antiproton Accumulator (AA). ATRAP, ATHENA and ASACUSA all use this stacking technique.

We were gratified at the widespread excitement that arose when ATHENA [19] and ATRAP [20, 21] reported observations of slow antihydrogen, produced during the positron-cooling of antiprotons that ATRAP had developed and demonstrated earlier[22]. Such excitement had not been seen since nine antihydrogen atoms were originally observed at LEAR [23], 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 [24, 25].

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 practised 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, but instead is generally limited almost entirely by systematic uncertainties.

Many other examples can be given, such as the extremely accurate hydrogen spectroscopy experiments by an ATRAP collaborator who was recognized by the most recent Nobel prize, and the electron magnetic moment measurements, and the fine structure constant measurements made recently by others in our collaboration.

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 working at 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) from which we grew proposed to accumulate antiprotons at an energy 10^{10} times lower than the lowest storage energy in the Low Energy Antiproton Ring, and to listen to the radio signal of a single antiproton as a way of comparing antiproton and proton 45,000 time more accurately than had been done before. Despite the experience and expertise of the original collaboration, techniques demonstrated with matter particles had to be adapted for the very different circumstances under which antimatter particles were available. 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 Goals and Milestones

1. 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 has done this for a small trap. More needs to be done when much larger traps are introduced.
   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 positron during antiproton experiments.
   Reference: ATRAP Members, Phys. Rev. Lett. **84**, 859 (2000).
   Reference: ATRAP, Phys. Lett. B 507, 1.

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 [14]. After earlier experiments [16] in which we used electrons to cool protons in a nested Penning trap [14], we demonstrated that this could also be done with positron and antiprotons – as needed to make antiprotons and positron interact at low relative velocities to produce slow antihydrogen.
   Status: Both ATRAP and ATHENA now use this technique to produce slow antihydrogen, using different methods to detect the antihydrogen.
   Reference: ATRAP, Phys. Lett. B 507, 1.

4. **Develop methods to produce antihydrogen during positron cooling of antiprotons.**
   Status: Both ATRAP and ATHENA 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 method which probes the internal structure of antihydrogen atoms, showing the 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, Phys. Rev. Lett. **92**, 133402 (2004).

7. **Develop a method to measure the energy of the antihydrogen produced during the positron cooling of antiprotons.** It is crucial to measure the velocity of antihydrogen atoms to make it possible to optimize the amount of antihydrogen that is moving slowly enough to be confined in a magnetic trap.
   Status: The observed antihydrogen has an 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.
   Reference: ATRAP, Phys. Rev. Lett. **93**, 73401 (2004).

8. **Develop methods to produce antihydrogen using a field-assisted formation method [26].**
   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 from Garching (now also 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 is likely 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. Larger traps and larger numbers of particles seem to be required.

13. **Develop methods to reduce the kinetic energy of antihydrogen atoms produced during positron-cooling of antiprotons.** It seems like the nested Penning trap should be capable of producing much lower energy antihydrogen atoms than have been observed so far.

14. **Develop methods to deexcite the internal state of antihydrogen atoms produced during laser-controlled charge exchange collisions.** Larger positron plasmas should make it possible to collionally deexcite antihydrogen atoms to lower excited states.

15. **Develop methods to reduce the kinetic energy of antihydrogen atoms produced during laser-controlled charge exchange collisions.** A higher antihydrogen production rate is required.

16. **Develop methods to produce ground state antihydrogen directly by using CO_2 lasers to stimulate the antihydrogen formation,** as we proposed long ago [14].
    Status: This method was tried by ATHENA, but has not worked 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 already in place at CERN. An entirely new trap apparatus is being constructed at Harvard, and will soon be commissioned at the AD.

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: An entirely new apparatus is being constructed at York University, of the same type used at ATHENA, and will soon be commissioned at the AD.

20. **Develop methods to image antiproton annihilation distributions in real time.** Status: A three-layer, scintillating fiber detector for antiproton annihilations has been constructed at the Juelich laboratory, and will soon be commissioned at the AD.

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 [15], and both ATRAP and ALPHA are pursuing this goal. 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. For many years we have calculated the properties of magnetic traps.
Status: The ATRAP II apparatus has space available for a magnetic trap, and the design and construction of such traps is being carried out at Harvard and Jülich.
Reference: ATRAP Members, Phys. Rev. Lett. **86** 5266 (2001).

22. **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 is under construction at Harvard and at Mainz.
Reference: ATRAP Member, Phys. Rev. Lett. **94**, 113002 (2005).

23. **Develop methods to confine antihydrogen atoms in a magnetic trap.**

24. **Develop methods to deexcite trapped antihydrogen atoms.** Our first focus is upon much larger positron plasmas to allow more collisional deexcitation.

25. **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: Good prospects for increasing the power and decreasing the size of a continuous, Lyman alpha source are being pursued at Mainz, with expectations of substantial success during this year.

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

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

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

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

30. **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.

31. **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.

32. **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.

2. Objectives and Focus for 2006

Much of the ATRAP effort in 2006 will be upon commissioning an entirely new apparatus. When we had no choice but to suspend the ATRAP program at the AD for one year, we decided that we could take best advantage of the one-year shutdown by building up an entirely new apparatus – one large enough to have ready access for lasers, and large enough to include a magnetic trap. While we are quite sure that the new apparatus, with its much larger electrodes and lower magnetic field, will greatly enhance our antihydrogen studies, it will certainly take some time to adapt the new methods developed over the last several years to the new environment. We hope to accumulate more antiprotons, and a very much larger number of positrons, with the goal of producing more antihydrogen atoms in less excited states, and moving more slowly.

During 2006 we will naturally push as hard as we can to achieve the next milestones. The crucial next steps involve deexciting the highly excited antihydrogen states that can be formed in large numbers, and producing antihydrogen atoms (using the nested Penning trap method) that are moving more slowly. In parallel, we seek explore methods to add the magnetic fields of a magnetic trap without destroying the production of antihydrogen atoms.

Our more specific objectives for 2006:

1. Commission an entirely new set of Penning traps, with much larger particle acceptance, a much larger particle storage volume, despite a much lower magnetic field (needed for compatibility with antihydrogen traps) with a field dependence to be determined.

2. Commission a gas-cooling positron source and positron guide line able to rapidly fill our larger Penning traps.

3. Commission a three layer scintillating fiber detector for real-time imaging of antiproton annihilations.

4. Determine the effect of magnetic trap fields upon the life times of the antiprotons and positrons used to produce antihydrogen, upon the transport of these charged particles into a nested Penning trap for antihydrogen production, and upon the antihydrogen production rate.

5. If possible, we would like to look for trapped antihydrogen atoms this year, but it is not clear that we will be have enough time to get this far. Such traps are in various stages of design and construction.

To be realistic, we must keep in mind the special technical challenges for 2006 – the need to restart a storage ring that has not been operated for a year and one half, an entirely new ATRAP apparatus, and a shorter-than-usual AD run.

3. Reminder of Requirements

A larger ATRAP II apparatus was forseen from the beginning of ATRAP, and was discussed in the original ATRAP proposal. To this end, collaboration members funded the installation of beam line elements and an experimental zone to which antiprotons can be delivered to a large solenoid. The commissioning of this larger apparatus has two requirements to be reminded of.

1. Details of the large fringing field for a large diameter solenoid were long ago provided to the AD team so that they could ensure that this fringing field did not adversely affect the transfer of antiprotons to ATRAP and other AD experiments. Because the ATRAP II solenoid was not commissioned as early as had been planned (owing to construction delays) the AD staff has again been provided with the fringing field values, and intends to have a shielding solution in place for 2006.

2. The need for a larger Penning trap requires a new positron source capable of filling this larger trap. There is a good location on top of the storage ring itself for this source, which is easily shielded and accessible. The positrons will be transferred to the ATRAP II zone by a positron wave guide – a technique that has been demonstrated to be reliable in previous low energy positron experiments. There is no special radiation requirement once the tiny radioactive source is locally shielded. We are, of course, discussing the appropriate procedures with CERN radiation safety officials.

A sketch of the proposed location and the positron guide tube is in Fig. 4.

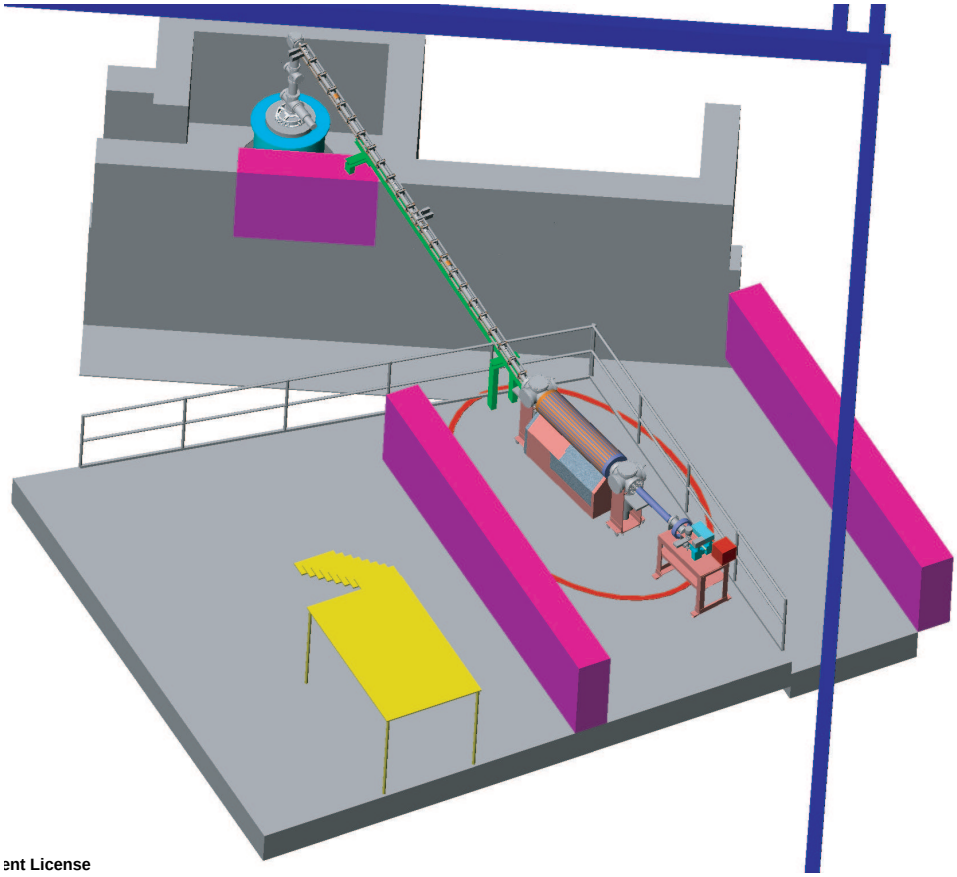

Figure 4: A convenient positron source location.

4. Antiproton Beam Request

We request an eight hour antiproton shift at the CERN AD for each day that the AD is operating during 2006. We certainly wish for much more beam time, because we could make more progress with more time, but understand that this is not possible this year. (See the discussion of p. 9). It is already very difficult to make experimental progress with such limited beam time. We urge the SPSC to resist any reduction to the number of antiprotons provided for antihydrogen research for fear of slowing the antihydrogen progress to an unacceptably low level.

D. 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 – up to 2×10^4 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 currently 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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