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The Production and Study of Cold Antihydrogen

by the
Antihydrogen TRAP Collaboration (ATRAP)

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A. Very Recent Relevant Publications by ATRAP and its Members

1. "New Interpretations of Antihydrogen Velocity Measurements and Field Ionization Spectra"
   T. Pohl, H.R. Sadeghpour and G. Gabrielse,
   Phys. Rev. Lett. **97**, 143401 (2006).

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. (in press).

3. "Density and Geometry of Single Component Plasmas",
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   (submitted for publication).

   Other publications are nearly ready for submission.

B. Overview

1. Introduction

The ATRAP Collaboration is glad to be back at CERN to continue 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. We are grateful to the SPSC for its efforts to facilitate this research.

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.

To mitigate the serious disruption to the antihydrogen research caused by the need to shut down CERN for one year, 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 and make room for magnetic traps, 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 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.

The schedule this year was challenging, with the time schedule turning out to be quite different than was anticipated and planned for – not so surprising given the previous year inactivity of the PS and the AD. For a time it looked like the very short beam year of 13 weeks was going to be even shorter, and that very little would be accomplish. In the end, however, we did commission a very substantial new apparatus. The ATRAP II platform works very well, though the limited access to antiprotons means that the effect of tuning many apparatus parameters remains to be seen. The unexpected antiproton delays gave us the opportunity to rearrange our priorities for the year, 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 is being reported in Physical Review Letters [1]

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 [2, 3].

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 [4]. 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 [5], interpreted as a comparison of magnetic moments at 2×10^{-12}. A single meson CPT test is

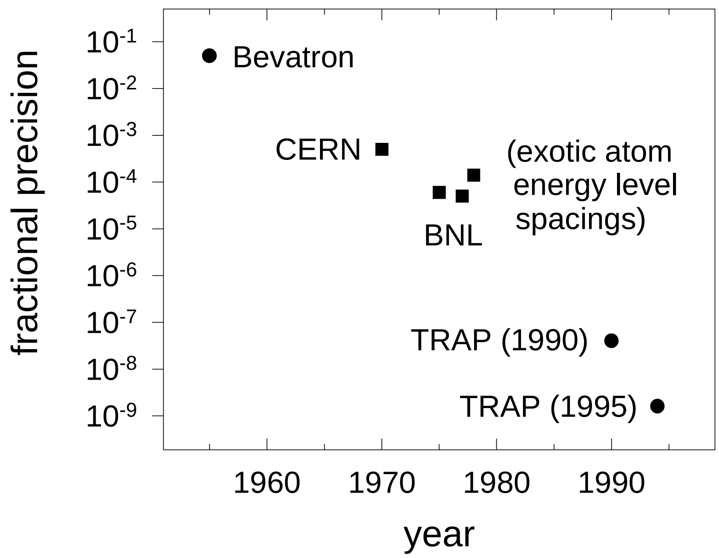

Figure 1: The accuracy at which antiprotons and protons have been compared.

even more precise [6]. 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 [2] 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.

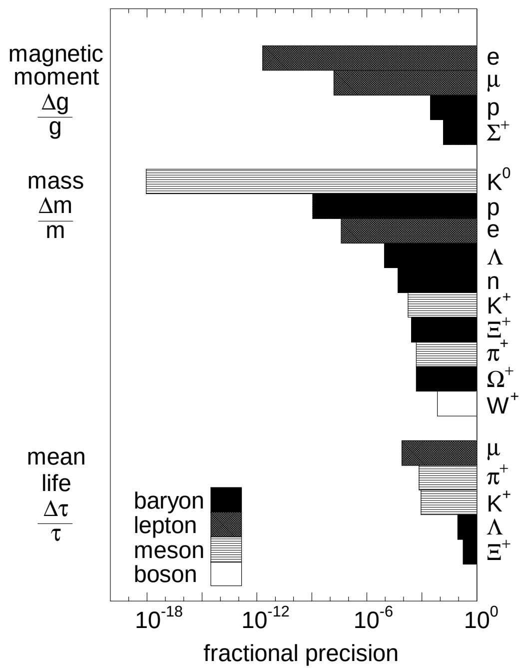

Figure 2: Tests of CPT Invariance. The particle-antiparticle pair is identified on the right. The shading indicates whether the comparison involves leptons, mesons or baryons. The accuracy achieved in the comparison is indicated below. Charge-to-mass ratio comparisons are included in "mass" measurements.

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 [7]. 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 [8], 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 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.

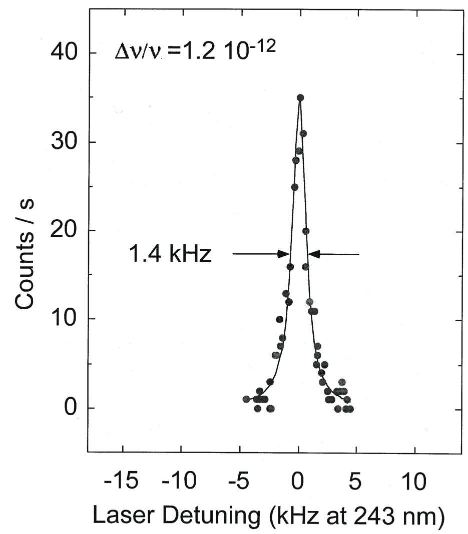

Figure 3: Narrow resonance line of the $1s - 2s$ $(F = 1)$ transition in hydrogen.

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 [9]. 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 [10], and routinely time the free fall of cold atoms released from a trap [11]. 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 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 [12], and then electron-cooled to 4 K [13, 14]. 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 [14]. 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 [15], and currently being pursued by ATRAP and ATHENA – cold antihydrogen stored in a magnetic trap for precise measurements [16]. 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 [17]. Before LEAR closed, modest numbers of cold positrons and cold antiprotons have already been stored together and made to interact [18]. The TRAP collaboration has demonstrated that successive pulses of such antiprotons can be accumulated within a trap [13, 14, 19], 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 [20] and ATRAP [21, 22] reported observations of slow antihydrogen, produced during the positron-cooling of antiprotons that ATRAP had developed and demonstrated earlier[23]. Such excitement had not been seen since nine antihydrogen atoms were originally observed at LEAR [24], 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 [25, 26].

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. Long Term 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 (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 [15]. After earlier experiments [17] in which we used electrons to cool protons in a nested Penning trap [15], 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 (2001).

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. A recent hypothesis suggests that this

is due to charge exchange.
Reference: ATRAP, Phys. Rev. Lett. **93**, 73401 (2004).

8. **Develop methods to produce antihydrogen using a field-assisted formation method [27].**
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 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 [15].
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.

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 substantial apparatus constructed at York University, of the same type developed at Bell Labs and used at ATHENA, has been commissioned at the AD. A more intense source and positron moderator should soon substantially increase the positron intensity. A positron guide has transported positrons up to the ATRAP II solenoid.

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. Limited antiproton availability did not allow the time needed to test the detector in much detail.

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 [16], 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 a quadrupole trap was carried out at Harvard and Jülich. Initial tests are very encouraging.
Reference: ATRAP Members, Phys. Rev. Lett. **86** 5266 (2001).
Reference: ATRAP, Phys. Rev. Lett. (in press).

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. The Harvard apparatus has been tested with electrons.
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 a substantial power increase very soon.

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. How Did We Do: Comparing ATRAP Objectives and Accomplishments for 2006

What follows is the ATRAP plan as reported to the SPSC last year, compared to the actual status at the end of 2006.

Much of the ATRAP effort in 2006 will 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.
   Status: The commissioning was very successful, with much more robust antiproton loading and much improved electron-cooling with photoelectrons.

2. Commission a gas-cooling positron source and positron guide line able to rapidly fill our larger Penning traps.
   Status: What a year ago was empty space is now a gas-cooled positron accumulator that works well, and awaits a stronger radioactive source and a neon moderator. The positron guide works well but has only been tested up to the ATRAP II solenoid before we decided to finish 2006 with an intense push to investigate antiproton stability when a Ioffe trap magnetic field was added.

3. Commission a three layer scintillating fiber detector for real-time imaging of antiproton annihilations. **Status:** A three-layer, scintillating fiber detector for antiproton annihilations, constructed at the Juelich laboratory, was commissioned at the AD. Limited antiproton availability did not allow the time needed to test the detector in much detail.

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. **Status:** This was a “long shot” for 2006, but we managed to do this late in the year. The ATRAP

II apparatus has space available for a magnetic trap, and the design and construction of a quadrupole trap was carried out at Harvard and Jülich. Initial tests, reported in PRL, are very encouraging. A copy of this short report is included as part of this report.

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. **Status:** Not attempted in 2006.

3. Inevitable Interactions of AD Experiments.

We recommend that the SPSC endorse five basic principles:

1. No experiment will connect directly to the AD vacuum in a way that allows vacuum glitches in the experiment to set off the emergency shut off valves on the AD beam lines. (This is a return to the AD policy.)

2. Each experiment will monitor the pressure of the shared helium recovery line, and will make sure that helium transfers are conducted in a professional way so that the pressure does not exceed the the recommendation of the CERN helium staff.

3. Each experiment will have a position sensitive detector that they and the AD staff can use to determine the beam location at the experiment in one AD shot, to allow quick correction to account for normal drifts and small adjustments in the magnetic field environment made since the previous shift.

4. Experiments will make any occasional change to the magnetic environment during their own shift, and if a small adjustment in beam line tuning may be required shall inform the AD staff and the experiment that may be potentially involved.

5. The AD staff is encouraged to explore any solution that will reduce the time required for tuning AD beam lines at the beginning of each shift.

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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2007 ATRAP Beam Time Request and Experimental Program

24 weeks: June 2007 – October 2007

Before June

- Install new positron source (after nondestructive testing)
- Install neon moderato
- Positron transfer into antiproton Penning trap
- Characterize the needed electron and positron plasmas
- Complete backup Penning trap and dewar assembly
- Stability studies with electrons and with a Ioffe field
- Construct add-on pbar loading solenoid
- Repair pin-hole vacuum leak in magnetic trap dewar

June

- Tune parameters for pbar loading and electron-cooling
- Commission add-on pbar loading solenoid
- Simultaneous confine positrons and antiprotons
- Pbar stability studies continue with Ioffe field added
  (test whether Hbar can be produced in a nested Penning trap)

July

- Tune parameters to obtain most effective positron plasmas for
  Hbar production
- Study stability effect of pinch coils on pbars and positrons
- Tune parameters for Hbar production in nested Penning trap
- Begin studies of Hbar deexcitation – field ionization spectra
  as a function of positron plasma parameters
- Begin study of laser-controlled charge exchange Hbar production

August

- Tune parameters to increase Hbar production by charge exchange
- First look for Hbar trapping from the most promising of the two production methods (or both)

September

- Tune parameters to optimize Hbar production with Ioffe field applied
- Install new magnetic trap on backup apparatus

October

- As needed complete Hbar studies with charge exchange method within Ioffe field, looking for trapped Hbar signals
- Commission improved magnetic trap
- Tune trap parameters to maximize Hbar production within an added Ioffe field

Note: The availability of antiprotons and the very slow rate at which experiments can be done with few antiprotons, will likely limit our scientific progress for 2007

We need more antiprotons:

→ please extend the run year a long as possible

→ please build ELENA

Antiproton Stability in a Penning-Ioffe Trap for Antihydrogen

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Antiprotons ($\overline{\text{p}}$) remain confined in a Penning trap, in sufficient numbers to form antihydrogen ($\overline{\text{H}}$) atoms via charge exchange, when the radial field of a quadrupole Ioffe trap is added. This first demonstration with $\overline{\text{p}}$ suggests that quadrupole Ioffe traps can be superimposed upon $\overline{\text{p}}$ and e^+ traps to attempt the capture of $\overline{\text{H}}$ atoms as they form, contrary to conclusions of previous analyses.

PACS numbers: 36.10.-k

A long-term goal for $\overline{\text{H}}$ experiments is confining $\overline{\text{H}}$ in a magnetic trap for precise laser spectroscopy [1] – to compare $\overline{\text{H}}$ and H as a test for violations of CPT and Lorentz invariance [2] and for possible differences in the gravitational force on antimatter and matter [3, 4]. These objectives were recently reviewed [5], along with the two methods that produce $\overline{\text{H}}$ atoms – using a nested Penning trap [6–10] and using laser-controlled charge-exchange [11, 12]. The simplest approach is to superimpose the magnetic gradient needed to trap $\overline{\text{H}}$ atoms upon the uniform magnetic field used to store the $\overline{\text{p}}$ and e^+ from which $\overline{\text{H}}$ will form. The quadrupole Ioffe traps that confined H atoms [13] for extremely precise laser spectroscopy [14] should confine similarly-cold $\overline{\text{H}}$ atoms. However, three reports in this journal expressed concern as to whether the radial field of such magnetic traps would prevent $\overline{\text{p}}$ and e^+ from being trapped long enough to produce $\overline{\text{H}}$ atoms [15–17]. The last of these claimed that the radial field of such magnetic traps would keep $\overline{\text{H}}$ from being produced by any known $\overline{\text{H}}$ formation mechanism [17]. These studies focussed upon radial Ioffe fields, perpendicular to the axial magnetic field of the Penning trap, assuming that axial Ioffe fields added to trap $\overline{\text{H}}$ could always be made small at the location of the trapped charges.

We demonstrate here the stable confinement of $\overline{\text{p}}$ in a Penning trap, when the radial magnetic field of a quadrupole Ioffe trap destroys the axial symmetry. This first experimental study of such $\overline{\text{p}}$ stability is facilitated by the near-unit efficiency with which annihilation pions reveal $\overline{\text{p}}$ losses. More $\overline{\text{p}}$ remain confined in our Penning trap apparatus (Fig. 1) than are needed to use ATRAP's laser-controlled charge-exchange method to produce $\overline{\text{H}}$ [12]. The feasibility of also keeping the needed e^+ confined in this environment is demonstrated with electrons. Ioffe quadrupole traps thus seem to have a role in $\overline{\text{H}}$ experiments, despite contrary claims, though much remains to be optimized and studied when $\overline{\text{p}}$ eventually become available again.

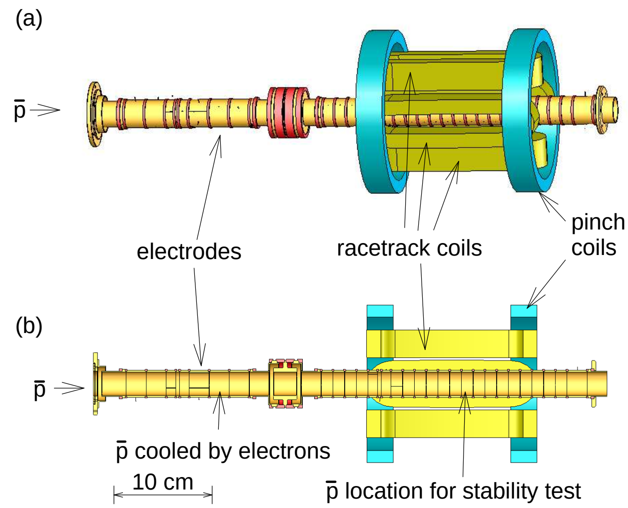

FIG. 1: Outside (a) and cutaway (b) views of a Penning-Ioffe apparatus. Many cylindrical ring electrodes can be biased to form Penning traps for antiprotons, positrons and electrons. An external 1 Tesla bias field, directed along the central symmetry axis of these electrodes, is produced by a large external solenoid (not shown). Two pinch coils add a gradient to the axial field. The radial quadrupole Ioffe field is produced by four racetrack coils.

There is a basic reason to fear charged particle loss

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from a Penning or Penning-Malmberg trap when the radial magnetic field of a Ioffe trap is added [15]. A confinement theorem [18] prevents radial particle loss from a cylindrically symmetric Penning trap – a spatially uniform magnetic field $B_0\hat{\mathbf{z}}$, and an electrostatic quadrupole potential $V \propto [z^2 - (x^2+y^2)/2]$. However, the axial symmetry, and the guaranteed radial confinement of charged particles, is destroyed by the addition of radial Ioffe fields.

One example is the radial field of a quadrupole Ioffe trap, $\beta(x\hat{\mathbf{x}} - y\hat{\mathbf{y}})$, with β determined by the geometry and current of the Ioffe trap. The field magnitude increases linearly with distance from the central axis, creating a field minimum that can radially confine a cold $\overline{\mathrm{H}}$ by its magnetic moment. Currents in four current bars (Fig. 2a) parallel to $B_0\hat{\mathbf{z}}$ produce such a field.

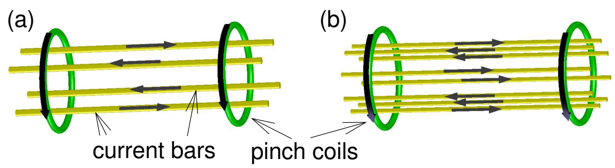

FIG. 2: Current bars of simple quadrupole (a) and octupole (b) Ioffe traps are parallel to an externally produced bias magnetic field. Currents in pinch coils add an axial gradient.

Higher-order Ioffe traps, produced using more current bars (e.g. Fig. 2b), offer smaller radial magnetic fields and gradients close to the center axis, lessening any gradient-related loss of $\overline{\mathrm{p}}$ confined near this axis [19]. However, quadrupole Ioffe traps offer several potential advantages. First, deeper radial well depths for $\overline{\mathrm{H}}$ are possible because the magnetic field magnitude for a quadrupole drops off much more slowly with increasing distance from the current bars than does that of a higher order trap, in the region just inside the current bars where electrodes and support materials must be located. Second, enhanced decay-induced cooling [20] may be possible. Third, there is easier radial access for cooling lasers. Fourth, tighter $\overline{\mathrm{H}}$ confinement to the center axis optimizes overlap with axial cooling and spectroscopy lasers.

Without axial symmetry and guaranteed radial confinement, what particle loss should be expected? In the absence of $\overline{\mathrm{p}}$ experiments, various answers have been offered. A report written to voice stability concerns [15] claimed that, in the absence of angular momentum conservation, adiabatic invariants could prevent radial loss of charged particles for low numbers and densities of charged particles, when a quadrupole Ioffe trap is added to a Penning trap. Resonances capable of causing particle loss seemed easily avoidable in the low density limit. As the particle density was increased, it was suggested that close collisions would eventually break these invariants and lead to particle loss, but the critical density could not be specified. A subsequent report [16] claimed that the resonances could not be avoided, and the resulting diffusive loss of charge particles would "very likely ... destroy the confinement of ... e^+ and $\overline{\mathrm{p}}$ ". A follow-up study with electrons [17] encountered electron loss along magnetic field lines that was more severe than the predicted diffusive loss. The strong conclusion was that quadrupole Ioffe traps "cannot be used to trap antihydrogen ... in all currently described [antihydrogen production] schemes."

The $\overline{\mathrm{p}}$ stability tests reported here use $\overline{\mathrm{p}}$ from the unique Antiproton Decelerator (AD) of CERN. They are captured in the lower section of a series of 45 cylindrical, gold-plated copper ring electrodes, each with a $R = 1.8$ cm inner radius. A spatially uniform magnetic field, $B_0 = 1$ T, is directed along the symmetry axis of the rings. This relatively low field is needed to avoid reducing the well depth for the Ioffe trap, even though 4.5 times more $\overline{\mathrm{p}}$ can be trapped per AD injection for $B_0 > 3$ T. Still, more than 30,000 $\overline{\mathrm{p}}$ slow in a degrader, are captured in the Penning trap and cool via collisions with cold electrons, for each $\overline{\mathrm{p}}$ injection. These are photoelectrons liberated from a thin gold layer by 10 ns, 1.7 MW excimer laser pulses at 248 nm. More $\overline{\mathrm{p}}$ are "stacked" if needed from successive AD injections [22]. The cooling electrons are released by removing the $\overline{\mathrm{p}}$ trapping potential for a time short enough that they, but not the $\overline{\mathrm{p}}$, can escape. For this test, the ejection was not optimized to ensure a $\overline{\mathrm{p}}$ temperature near the 4.2 K of the apparatus.

The $\overline{\mathrm{p}}$ are transferred through the series of cylindrical electrodes, from the place where they are initially electron-cooled (Fig. 1b) to an electrode near the center of the de-energized quadrupole Ioffe trap (Fig. 1b), a move of 0.4 m through 18 electrodes. They are transferred adiabatically through one electrode at a time by manipulating the potentials applied to the electrodes. More $\overline{\mathrm{p}}$ loss is detected during the transfer than expected, a likely consequence of an elevated $\overline{\mathrm{p}}$ temperature. The $\overline{\mathrm{p}}$ are held as long as desired. When released from the trap, their annihilations are counted as the $\overline{\mathrm{p}}$ strike the degrader plate (used earlier to slow $\overline{\mathrm{p}}$ for their initial capture). Four layers of scintillating fibers and two layers of plastic scintillator paddles detect the annihilations with a high efficiency, and counting coincidences from these detector layers reduces the background.

The radial field of the quadrupole Ioffe trap is produced by current in the superconducting current bars of racetrack coils (Fig. 1). Current sent through superconducting pinch coils would produce the axial gradient needed to axially confine $\overline{\mathrm{H}}$, adding to B_0 and making it depend upon z. Fields and critical currents for the magnetic trap were initially calculated at Harvard, where the cryogenic platform and Penning traps were designed and built. The final magnetic trap design, mechanical stability, and construction were the responsibility of the Jülich team [23]. Multi-strand NbTi wire is wound on titanium forms. Strong outward forces after energization are contained by close fitting titanium parts and aluminum bands. The Ioffe trap is designed so that 69 A in the racetracks and 80 A in the pinch coils produce a gradient $\beta = 0.93$ T/m, a radial-to-axial field ratio $\beta R/B_0 = 0.78$, and a 375 mK well depth for ground-state $\overline{\mathrm{H}}$ in an external 1 T field. (The trap depth is 650 mK without the

1 T.). Four magnesium fluoride windows provide optical access for future $\overline{\mathrm{H}}$ laser cooling and spectroscopy, even at the ultraviolet 121.5 nm $\overline{\mathrm{H}}$ Ly α wavelength.

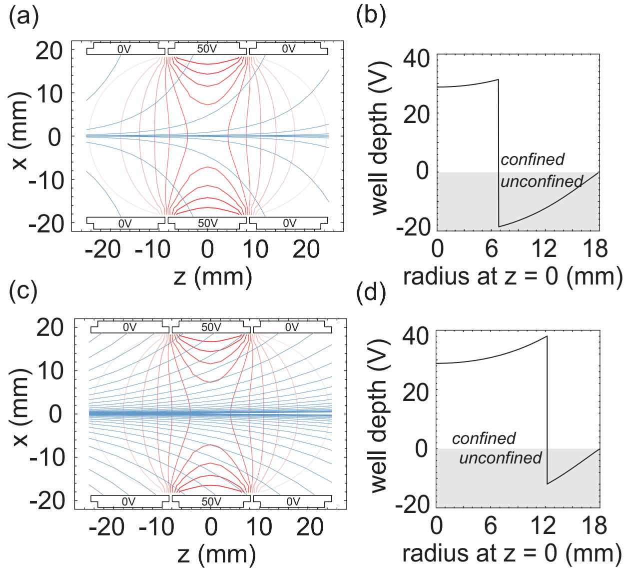

FIG. 3: Cross section of cylindrical ring electrodes (black) in which $\overline{\mathrm{p}}$ are stored, with superimposed magnetic field lines (blue) and electrostatic equipotentials in 5 V intervals (red). Magnetic field lines, without (a) and with (c) current in the pinch coils, diverge so as to intersect electrodes, even as they make a magnetic field whose magnitude increases with distance from the trap axis and center. The corresponding electrostatic well depth for a $\overline{\mathrm{p}}$ moving along a field line is represented in (b) and (d).

Fig. 3a represents the trap electrodes within which the $\overline{\mathrm{p}}$ are centered for the stability tests, with magnetic field lines of the radial Ioffe field and the bias field, along with equipotentials generated by applying 50 V between the electrodes. Field lines initially parallel to $\hat{\mathbf{z}}$ diverge to intersect electrodes when a strong Ioffe field is added. Fig. 3b shows the well depth for $\overline{\mathrm{p}}$ along various field lines, specified by their radial position at the center of the trap electrode ($z = 0$). The well depth increases slightly for field lines that are displaced radially from the trap center, out to an abrupt cutoff that occurs for field lines that intersect the center electrode. There is no potential well along such field lines. We would thus expect any $\overline{\mathrm{p}}$ confined out at a larger radius to be lost when the Ioffe field of Fig. 3a is applied, and that radial compression methods (not used in this work) could reduce $\overline{\mathrm{p}}$ loss. Fig. 3c-d pertains when the pinch coils are also energized. The useful trapping radius for $\overline{\mathrm{p}}$ doubles as the pinch coils double the bias field.

To test for $\overline{\mathrm{p}}$ stability, the radial magnetic field of a quadrupole Ioffe trap is applied after $\overline{\mathrm{p}}$ have been centered within it. The Ioffe field is ramped up (over about ten minutes at 0.1 A/s), held constant for five minutes (enough time to make $\overline{\mathrm{H}}$ via the charge-exchange method), and then ramped back to zero, while $\overline{\mathrm{p}}$ annihilation detectors monitor $\overline{\mathrm{p}}$ loss. The surviving $\overline{\mathrm{p}}$ are released from the trap and counted. Fig. 4 shows that the fraction of $\overline{\mathrm{p}}$ that survive a quadrupole Ioffe field decreases linearly with radial quadrupole current. The loss may be less if the axial $\overline{\mathrm{p}}$ temperature is reduced, by optimizing the electron ejection, and/or by introducing cooling electrons into the $\overline{\mathrm{p}}$ trap. Already, more $\overline{\mathrm{p}}$ survive than needed to produce $\overline{\mathrm{H}}$ via charge exchange.

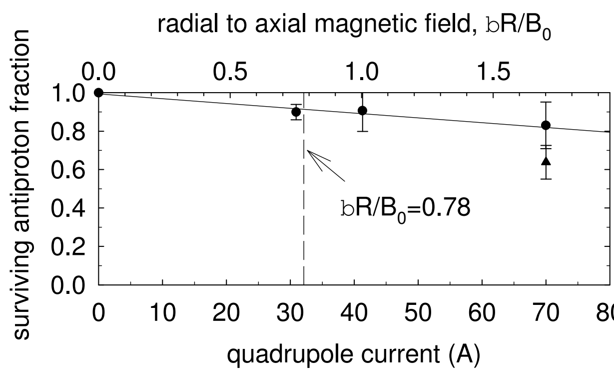

FIG. 4: Fraction of about 90,000 (circles) and 280,000 (triangle) trapped $\overline{\mathrm{p}}$ that survive a radial Ioffe quadrupole field that is ramped up to a given current, held 300 s, and ramped back down.

The other requirement for $\overline{\mathrm{H}}$ formation via charge exchange is that e^+ must be confined near the trapped $\overline{\mathrm{p}}$, and hence must also survive the radial field of a Ioffe trap. For a test we substitute electrons which we expect to initially radiate synchrotron radiation to equilibrate at 4.2 K. After loading and transferring 36 million electrons into the center of the Ioffe trap, the radial Ioffe field is slowly ramped on, held constant, and then ramped off, just as described above for $\overline{\mathrm{p}}$. As for $\overline{\mathrm{p}}$, we expect electrons outside of the cutoff radius of Fig. 3b will be lost. Still, the number of electrons remaining in the trap (Fig. 5) is more than the number of e^+ needed for $\overline{\mathrm{H}}$ production via charge exchange, even at $\beta R/B_0 = 1$. The electron survival is substantially larger than observed earlier [17] for our highest radial fields, perhaps because of differences in unspecified electrostatic well depth and/or plasma temperature. The longer plasmas mostly used in the earlier study showed much larger losses.

Our principal focus, like that of the earlier reports [15–17], is on the effect of the radial quadrupole Ioffe field for two reasons. First, the axial Ioffe fields from pinch coils are axially symmetric. Second, it should be possible to reduce any $\overline{\mathrm{p}}$ losses associated with these fields by relocating the pinch coils farther from the $\overline{\mathrm{p}}$ trap. Still, the pinch coils will likely have some effect. For example, increasing the current in pinch coils should adiabatically increase the $\overline{\mathrm{p}}$ cyclotron energy, raising the $\overline{\mathrm{p}}$ temperature due to $\overline{\mathrm{p}}$ - $\overline{\mathrm{p}}$ collisions. The effect of axial gradients must be studied experimentally when $\overline{\mathrm{p}}$ are next available.

What else is required to trap $\overline{\mathrm{H}}$ atoms produced by charge exchange? First is an $\overline{\mathrm{H}}$ kinetic energy less than the trap depth (375 mK here). The energy of the $\overline{\mathrm{H}}$ is

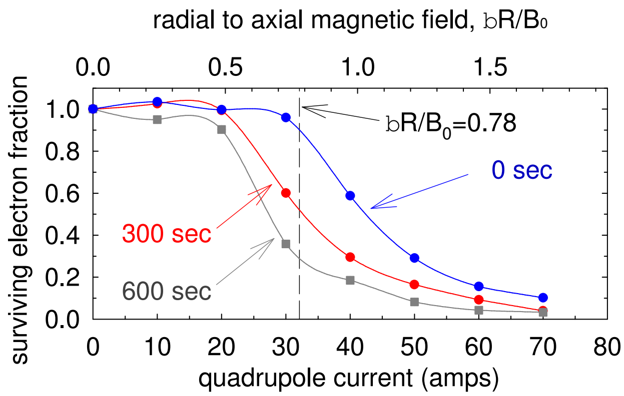

FIG. 5: Fraction of electrons that survive a radial Ioffe quadrupole field that is ramped up to a given current, held 0, 300 or 600 s, and ramped back down.

expected to be essentially that of the $\overline{\text{p}}$ from which they form, for this production method. For $\overline{\text{H}}$ formed from 4 K $\overline{\text{p}}$, a small number of $\overline{\text{H}}$ from the tail of a thermal distribution would have such low energies. Second, the $\overline{\text{H}}$ states must have magnetic moments that are sufficiently large and properly oriented to be trapped. The moments of the highly-excited $\overline{\text{H}}$ atoms formed [5, 10] have not been measured, and it is not known if any ground-state atoms are produced. We remain intrigued by the possibility that some of the highly-excited, highly-polarizable $\overline{\text{H}}$ states will be trapped [10], and remain so as radiation [20] slowly reduces the internal $\overline{\text{H}}$ energy.

Finally, can a quadrupole Ioffe trap superimposed upon a nested Penning trap [6] be used to capture $\overline{\text{H}}$ produced during positron cooling of antiprotons [7] in a nested Penning trap [6] – the most commonly used of the two methods to produce slow $\overline{\text{H}}$ [7–10]? A recent reinterpretation [24] of $\overline{\text{H}}$ velocity measurements [25] suggests that $\overline{\text{H}}$ atoms cold enough to trap may already be produced by this formation method. As a first step toward understanding whether such $\overline{\text{H}}$ formation is compatible with a quadrupole Ioffe trap, we are encouraged that many $\overline{\text{p}}$ and electrons survive being moved adiabatically along the bias field direction within the radial Ioffe field for several cm. However, remaining stability questions await experimental answers when $\overline{\text{p}}$ are next available.

In conclusion, substantial numbers of $\overline{\text{p}}$ survive the effect of the radial magnetic field of a quadrupole Ioffe trap – enough to produce $\overline{\text{H}}$ atoms within this field using the charge-exchange method for $\overline{\text{H}}$ production. Substantial numbers of e^+ can be stored in the appropriate location within the Ioffe field based upon a demonstration with electrons. Quadrupole Ioffe traps thus seem to have a role to play for $\overline{\text{H}}$ formed by charge exchange, in spite of earlier claims to the contrary. Whether they have a role to play in trapping $\overline{\text{H}}$ produced in a nested Penning trap remains to be seen.

We are grateful to CERN and the AD team for delivering the 5 MeV energy antiprotons. This work was supported by the NSF and AFOSR of the US, the BMBF, DFG, and Jülich Laboratory of Germany, along with the NSERC, CRC, CFI and OIT of Canada.

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