The Production and Study of Cold Antihydrogen

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

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Contents

A. Accomplishments and Aspirations 3
  1. Introduction to Methods and Objectives .......................... 3
  2. Papers for 2010 (Attached) ........................................ 3
  3. ATRAP Conclusions and Accomplishments in 2010 .................. 4
  4. Goals Not Realized in 2010 ............................................ 4
  5. Objectives for 2011 ..................................................... 5

B. ATRAP Milestones ..................................................... 6

C. Background 11
  1. CERN's Unique AD has Allowed Great Progress and Excitement 11
  2. Not the Usual CERN Experiment ..................................... 11

D. The Flux Challenge and Solution 13
  1. We Cannot Succeed Without Antiprotons .......................... 13
  2. The ELENA Advantage ............................................... 13

E. References .......................................................... 14

F. Attached Papers ..................................................... 15
A. Accomplishments and Aspirations

1. Introduction to Methods and Objectives

The proposal to make cold antihydrogen using cold, trapped antiprotons was written down by some of us back in 1987 [1], not long after our TRAP collaboration trapped the first antiprotons [2]. The production of antihydrogen cold enough to capture in a neutral particle trap for precise laser spectroscopy was also proposed at the same time.

The basic antiproton methods now used by all antihydrogen collaborations were subsequently developed by the TRAP collaboration which evolved into ATRAP. Antiprotons were slowed in matter and trapped with the sudden application of a potential [2]. The antiprotons were then cooled with electrons to produce antiproton energies about $10^{10}$ times lower than had previously been produced. Antiproton accumulation (called stacking) was demonstrated soon after [3] and later reported in detail [4]. CERN’s Antiproton Decelerator (AD) was built so that the antihydrogen aspirations could be realized. Three, soon to be four, collaborations now are approved by the SPSC for antihydrogen experiments.

ATRAP first searched for trapped antihydrogen atoms in 2008 [5], achieving a background low enough to allow the detection of about 20 trapped antihydrogen atoms – an upper limit on the number of atoms that we were producing using three-body recombination within a nested Penning trap [6]. Our conclusion, one we still stand by, was that many more antiprotons at much lower temperatures are needed to realize the proposal that useful numbers of antihydrogen atoms be trapped for precise laser spectroscopy.

Obtaining substantially more cold antiprotons was thus a primary ATRAP goal for 2010. We did not seek to increase our detection sensitivity, increase our ability to detect very briefly trapped atoms, or to average long times to detect very small numbers of briefly trapped atoms. The progress that we made with cold antiprotons will hopefully be used to advantage for antihydrogen production in 2011. The aspirations thus arise directly from the accomplishments.

2. Papers for 2010 (Attached)


The short papers have the appropriate level of detail for this progress report, and hence are attached as part of this progress report. The summary pages of the longer technical paper are also attached.
3. ATRAP Conclusions and Accomplishments in 2010

1. ATRAP cooled large enough numbers of trapped antiprotons to a low enough temperature to demonstrate for the first time the first radial separation of trapped antiprotons from the electrons used to initially cool them. This is discussed in an attached Physical Review Letter.

2. ATRAP demonstrated that temperatures as low as 3.5 K could be directly measured and realized. This is three times lower than any other directly determined antiproton temperature. It is discussed in an attached manuscript that is currently under review.

3. Embedded electron cooling (with antiprotons greatly outnumbering the electrons used to cool them) was used to cool large numbers of antiprotons (up to $3.5 \times 10^6$) to 17 K. This is discussed in an attached manuscript that is currently under review.

4. Adiabatic cooling was used with up to $3.5 \times 10^6$ antiprotons to realize temperatures measured to be 3.5 K or lower. This is discussed in an attached manuscript that is currently under review.

5. Despite the declining activity of our radioactive source (what was originally 52 mCi is now 17 mCi) the positron accumulation efficiency continues to increase as we learn how to better operate and tune the accumulator and transfer line. Positrons now accumulate in our accumulator at a rate of $4 \times 10^4 e^+/s/mCi$, and in the antihydrogen trap at a rate of $1.5 \times 10^4 e^+/s/mCi$. Up to $3.8 \times 10^9$ positrons have been collected in the Penning traps where antihydrogen is made though smaller numbers were typically used in 2010.

6. The technical problems with getting sufficient Cs atoms in a cryogenic environment were solved, with one Cs source used for the entire 2010 antiproton run. The instability of the antihydrogen ingredients during antihydrogen production was also solved.

7. Antihydrogen was produced by laser-controlled charge exchange with much larger numbers of trapped antiprotons and positrons than when we first demonstrated this method [7] with small numbers of antiprotons and positrons. (Tentative conclusion still under study.)

8. Large traps and large numbers of antiprotons and positrons make it difficult to use the ATRAP field ionization method for detecting antihydrogen production.

9. The first one-proton self-excited oscillator was demonstrated. The frequency resolution achieved was nearly what is required to observe and proton or antiproton spin flip, as needed to improve the comparison of the antiproton and proton magnetic moments by a factor of a million or more. This is discussed in an attached Physical Review Letter.

4. Goals Not Realized in 2010

Time did not permit reaching several goals for 2010.

1. There was not time to look for molecular antihydrogen.

2. There was not time to finish the new Ioffe trap and commission it. This is a high priority for 2011.
5. **Objectives for 2011**

The objectives for 2011 derive directly from what was accomplished in 2010.

1. Commission and use the new Ioffe trap that we have previously described to the SPSC.

2. Use the much larger number of much colder antiprotons to make antihydrogen in a nested Penning trap and see how much of it can be trapped.

3. Continue the investigation of laser-controlled charge-exchange production of antihydrogen, and see if atoms that can be trapped are being produced.
B. ATRAP Milestones

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

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

2. **Develop methods to fill a small trap with positrons.** We developed the first method to load large numbers of positrons into a cryogenic trap at high field.
   - **Status:** Up to 5 million positrons were accumulated – enough to fill a small Penning trap to its useful limit. Great care was required to reuse the positrons during antiproton experiments.

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 [6]. After earlier experiments [8] in which we used electrons to cool protons in a nested Penning trap [6], we demonstrated that this could also be done with positrons and antiprotons – as needed to make antiprotons and positrons interact at low relative velocities to produce slow antihydrogen.
   - **Status:** Both ATRAP and ALPHA now use this technique to produce slow antihydrogen, using different methods to detect the antihydrogen.

4. **Develop methods to produce antihydrogen during positron cooling of antiprotons.**
   - **Status:** Both ATRAP and ALPHA now regularly use this method to produce antihydrogen.

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.

6. **Develop methods to measure the internal structure of antihydrogen atoms.** So far the ATRAP field ionization method is the only probe of the internal structure of antihydrogen atoms, showing that most or all of the antihydrogen atoms observed so far are in highly excited internal states.

7. **Develop a method to measure the energy of the antihydrogen produced during the positron cooling of antiprotons.** Low velocity antihydrogen atoms must be produced if they are to be confined in a magnetic trap.
   - **Status:** The observed antihydrogen has a measured energy that is higher than we had hoped, and we have not yet been able to demonstrate the lower energy antihydrogen that we think
that this method should be able to produce with careful tuning. A recent hypothesis suggests that this is due to charge exchange.


8. Develop methods to produce antihydrogen using a field-assisted formation method [9].
**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.

10. Develop methods to use lasers to control antihydrogen production via resonant charge exchange collisions. We used this method to first produce cold Rydberg positronium at Harvard, and then to produce what could be the first truly cold antihydrogen atoms at the AD.

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

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

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

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

15. Develop methods to reduce the kinetic energy of antihydrogen atoms produced during laser-controlled charge exchange collisions.
**Status:** More positrons are required to make more antihydrogen. These are now available, so this is one priority for the coming year. The demonstration of 1 K plasmas is a very important for this goal.
16. Develop methods to produce ground state antihydrogen directly by using CO₂ lasers to stimulate the antihydrogen formation, as we proposed long ago [6].
   Status: This method was tried by ATHENA, but without success (so far).

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

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

19. Develop methods to introduce the much larger numbers of positrons needed to fill our larger Penning traps. A different positron accumulation method is required to accumulate more than the 5 million positrons which filled our smaller traps.
   Status: A substantial apparatus constructed at York University, of the same type developed at Bell Labs [10] (and used at ATHENA), has been commissioned at the AD. A positron guide now regularly transports positrons to the ATRAP II solenoid. We now routinely start an antihydrogen production experiment with 60 million positrons.

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

21. Develop magnet traps and methods that prevent magnetic traps from causing the loss of accumulated positrons and antiprotons. Long ago we suggested that antihydrogen spectroscopy would be best carried out in a magnetic trap [1], and both ATRAP and ALPHA are pursuing this goal, and many calculations have been performed. The challenge is avoiding the loss of antiprotons and positrons before antihydrogen is made, and moving these particles into locations in which antihydrogen can be made, when a magnet trap is present.
   Status: The stable confinement of antiprotons in a Penning-Ioffe trap was demonstrated.

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

23. Look for the antimatter counterparts of H⁻ and H₂⁺. No one has ever looked for the production of these ions, even though extremely cold antihydrogen atoms could be produced by ionizing or dissociating these species, respectively.
   Status: We have demonstrated the detection sensitivity required to see one ion. We did not have enough time to pursue this during 2010.

24. Develop methods to measure the magnetic moment of a single trapped antiproton. If the spin flip of an antiproton can be detected nondestructively (a very challenging undertaking), then it should be possible to measure the magnetic moment of an antiproton more than a million times more accurately. We have discussed this exciting possibility with
the SPSC on several occasions, including the way that it would be done as a parasitic experiment at ATRAP.

Status: Apparatus to demonstrate the non-destructive detection of a proton spin flip has been built at Harvard and at Mainz. A single trapped proton is being studied at Harvard.


A one-proton self-excited oscillator was realized for the first time at Harvard. With it the frequency resolution needed to observe a proton (or antiproton) spin flip was demonstrated – an important step on the way to actually observing a proton spin flip.


25. Develop methods to confine antihydrogen atoms in a magnetic trap, and demonstrate that antihydrogen atoms have been trapped.

Status: We looked for trapped antihydrogen atoms first in 2008, setting a limit on the number that would need to be produced in a typical trial to be detected above the detection background. We decided that obtaining a usable number of trapped antihydrogen atoms would require obtaining many more antiprotons that were much colder. We thus spent much of 2010 pursing this goal.


26. Develop methods to get colder and larger numbers of trapped antiprotons.

Status: Much progress was made in 2010. Cold enough antiprotons were produced so that centrifugal separation of antiprotons and electrons was observed for the first time. The temperature of $3.5 \times 10^6$ antiprotons was directly measured to be 3.5 K or lower within a 1.2 K apparatus.


27. Investigate the charge exchange method for producing cold antihydrogen.

Status: ATRAP demonstrated this antihydrogen production method with relatively small numbers of antiprotons and positrons. The progress made in 2010 is still being analyzed. Antihydrogen was produced but could not be detected using our field ionization method.


28. Develop methods to deexcite trapped antihydrogen atoms.

Now that we have much larger positron plasmas to allow more collisional deexcitation we can turn our attention to this important issue.

29. Make a new version of the Lyman alpha source that has more power, and is also compact and robust enough to use at the CERN AD.

Status: Substantial performance gains in the 254 nm and 545 nm laser systems needed for the continuous Ly $\alpha$ source have been realized at Mainz, including the first Lyman $\alpha$ produced by the new system.


Reference: ATRAP Members, Optics Express **15**, 14476 (2007)).

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

31. Develop and demonstrate methods to use the coherent source of Lyman alpha radiation to cool trapped antihydrogen atoms.
32. **Develop methods to perform off-resonant two-photon spectroscopy of antihydrogen.** This offers a higher accuracy than 1s-2p spectroscopy, with a larger signal than does 1s-2s spectroscopy.

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

34. **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.

35. **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.

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

1. CERN’s Unique AD has Allowed Great Progress and Excitement

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

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

ATRAP grew out of the TRAP Collaboration (PS196) which developed the techniques to reduce the energy of antiprotons by more than a factor of $10^{10}$ below the energy with which they were delivered by LEAR (and the AD). TRAP developed and first demonstrated the techniques whereby antiprotons from LEAR are now routinely slowed in matter, trapped \[1\], and then electron-cooled to 4 K \[11, 3\]. 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 \[3\]. These slowing, trapping and cooling methods form the basis of experiments by ATRAP, ATHENA (now ALPHA and AEGIS) and ASACUSA at the AD.

Great progress has been made at the AD towards the antihydrogen research goals laid out long ago by members of the TRAP Collaboration \[6\], and currently being pursued by ATRAP and ALPHA – cold antihydrogen stored in a magnetic trap for precise measurements \[1\]. Electrons and protons in a nested Penning trap were used to demonstrate that oppositely charged species, like antiprotons and positrons, could be made to interact with a very low relative velocity \[8\]. Before LEAR closed, modest numbers of cold positrons and cold antiprotons had already been stored together and made to interact \[12\]. The TRAP collaboration demonstrated that successive pulses of such antiprotons can be accumulated within a trap \[11, 3, 4\], thereby providing a much less expensive alternative to CERN’s Antiproton Accumulator (AA). ATRAP, ATHENA and ALPHA all use this stacking technique.

We were gratified at the widespread excitement that arose when ATHENA \[13\] and ATRAP \[14, 15\] reported observations of slow antihydrogen, produced during the positron-cooling of antiprotons that ATRAP had developed and demonstrated earlier \[16\]. Such excitement had not been seen since nine antihydrogen atoms were originally observed at LEAR \[17\], 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 \[18, 7\].

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

2. Not the Usual CERN Experiment

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

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

Many other examples can be given for extremely precise measurements being realized after considerable time and effort. One is that the extremely accurate hydrogen spectroscopy experiments by an ATRAP collaborator who was recognized with the 2005 Nobel prize [19]. The recent electron magnetic moment measurement and the fine structure constant measurement made recently by another in our collaboration is another example [20].

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

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

1. We Cannot Succeed Without Antiprotons

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

2. The ELENA Advantage

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

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

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

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


F. Attached Papers
Angel and Demons, a bestselling book and popular movie, describes the theft of “trapped antimatter.” Not specified is whether what is trapped is the charged antimatter particles that my colleagues and I are proud to have first trapped at CERN or the neutral antimatter atoms that we hope to soon trap. In the story, sinister folks threaten to annihilate the trapped antimatter to blow up the Vatican and the cardinals assembled there to select a pope. The same distorted lens with which author Dan Brown disfigured the Roman Catholic Church in The Da Vinci Code was focused on our cold antiproton and antihydrogen research program in Angels and Demons. Brown made his millions untroubled by the fact that the simultaneous annihilation of all the antiprotons ever made would not release enough energy to boil a pot of tea. The movie’s camera zooms in on a part of CERN where no antimatter particles circulate and no antimatter will be trapped—the Large Hadron Collider (LHC).

The myth and the science
Trapped antimatter as popular mythology was not on my mind when, 23 years ago, I first asked CERN for a chance to slow, trap, and cool their antiprotons. The first goal of the TRAP collaboration, which I was privileged to lead, was to precisely compare the charge-to-mass ratios of the antiproton and proton. We demonstrated methods to accumulate cold antiprotons and realized the comparison with a precision of 9 parts in $10^{11}$. The second goal was to produce and study cold antihydrogen; when that goal became primary, we renamed the collaboration ATRAP. In view of initial skepticism at CERN about accumulating antiprotons 10 orders of magnitude lower in energy than ever before obtained, who could have predicted that CERN would eventually build a storage ring for cold antihydrogen studies and that four international collaborations would join the hunt for cold antihydrogen?

Those collaborations—ATRAP, ALPHA, ASACUSA, and AEGIS—now encounter their own angels and demons. The angels are the skilled accelerator physicists at CERN who built and operate the antiproton decelerator (AD) storage ring. Every 100 seconds, that tiny relative of the LHC provides 30 million 5-MeV antiprotons in a short pulse. The demons obstructing ATRAP and ALPHA are whatever is keeping the antihydrogen atoms that they are producing from moving slowly enough to be trapped efficiently and from decaying to their ground state before they escape the apparatus. (ASACUSA hopes to make antihydrogen soon, and AEGIS is designing its first apparatus.)

The scientific goal of cold antihydrogen studies is to precisely compare antihydrogen and hydrogen atoms to check if their structure or gravitational interactions differ. They will not if, as most physicists expect, reality is invariant under CPT transformations: interchange of particles and antiparticles (charge conjugation, C), inversion of the three spatial directions (parity, P), and reversal of motion (time reversal, T). Such invariance is an unavoidable consequence of the most successful theories in physics, axiomatic quantum field theories that are invariant under Lorentz transformations.

Simply assuming CPT invariance seems incautious since gravity has not been successfully incorporated into a quantum field theory. Also, we physicists once thought incorrectly that reality was invariant under P, and later incorrectly that it was invariant under CP. In the end, God decides and we measure. Precise and interpretable comparisons of the simplest atoms of antimatter and matter should produce the most stringent test of CPT’s symmetry with lepton and baryon particles. It would be wonderful if CPT violation were to be detected and contribute something to an explanation of the imbalance of matter and antimatter in the universe.

Two methods form slow antihydrogen
The building blocks of ATRAP’s apparatus, shown in figure 1, are similar to those of ALPHA. The antiprotons sent from the AD slow as they pass through a thin matter window and slow...
as they interact with electrons, the only matter particles unable to annihilate them. The process is rapid enough that annihilation with nuclei is minimal. Those slowed charges are captured in Penning traps—potential wells made by applying voltages to hollow metal electrodes and applying a magnetic field along their axis (see figure 2)—where they cool by colliding with simultaneously trapped electrons. Positrons from the decay of sodium-22 collide with atoms in a column of decreasing gas density and end up similarly trapped in the low-gas-density end of a positron accumulator. Tens of millions of the positrons are transferred to the Penning traps (figure 2) in two bunches delivered between antiproton pulses.

Most slow antihydrogen atoms are produced in a nested Penning trap, a device that several of us invented to allow trapped charges with opposite signs to interact. Since a potential well for antiprotons is a potential hill for the oppositely charged positrons, a nested trap is a potential well for antiprotons inside of which is a shallower inverted well that confines positrons. The positrons emit synchrotron radiation and, within minutes in a 1-T magnetic field, come to thermal equilibrium with the surrounding apparatus. The heavier antiprotons cool by colliding with the cold positrons. Those that cool to just the right energy can collide with two positrons to form an antihydrogen atom. The spectator positron enables conservation of energy and momentum. Several years ago ATRAP and ATHENA (now disbanded) both observed antihydrogen atoms produced in that way.

The ATRAP group also demonstrated a second, laser-controlled method to produce slow antihydrogen atoms. Infrared and green lasers put cesium atoms into highly excited states. Those Cs atoms collide with trapped positrons to form excited positronium atoms, bound states of a positron and an electron. A few of those collide with trapped antiprotons to form antihydrogen. The laser frequencies determine the excited state of the antihydrogen because the binding energy of the Cs atoms is approximately transferred to the positronium and then to the antihydrogen. The antihydrogen formed should have the temperature of the antiprotons since the light positronium atom does not transfer much momentum to the heavier antiproton.

Traps for antihydrogen and beyond

My initial proposal to trap antihydrogen atoms arose from the expectation that antihydrogen atoms would always be scarce and would thus be most efficiently studied if kept from drifting out of the apparatus. As subsequently demonstrated with hydrogen, an atom with a magnetic moment can be confined where there is a minimum in the magnitude of a magnetic field. A loffe trap uses currents in racetrack coils and pinch coils, as shown in figure 2, to make the field minimum.

The ATRAP and ALPHA collaborations recently produced antihydrogen atoms within loffe traps. They are looking for evidence that trapped atoms are released and annihilate when the traps are turned off fast enough to nearly eliminate the background signals from cosmic rays. The groups have seen only the very occasional intriguing signal but hope to soon produce useful numbers of trapped antihydrogen atoms.

A significant challenge is that the strongest loffe traps can confine only atoms whose energy is lower than 0.5 K. The atoms produced so far seem to be moving too rapidly to be trapped efficiently, and the likelihood of losing excited antihydrogen atoms from the trap as they decay to lower states is not well understood. ATRAP and ALPHA are now carefully studying the temperatures, densities, and spatial distributions of cold antiproton and positron plasmas to learn how to produce colder atoms.

At ATRAP we are encouraged by three recent developments. First, we can now use electron and positron plasmas with temperatures approaching 1 K to cool antiprotons. If we could produce antihydrogen atoms at that temperature, a substantial fraction of them could be confined in a trap 0.5 K deep. Second, every hour as many as 5 million cold antiprotons and 100 million or more positrons are available for making antihydrogen. Third, we have recently demonstrated the sensitivity required to detect a single antimatter counterpart of H+ and H2+ ions, should a few of those be produced in the antihydrogen apparatus. The ALPHA group uses high-temperature plasmas and many fewer antiprotons to form the atoms than ATRAP does, but attempts to trap atoms more frequently. ALPHA relies on position-sensitive detectors as well as upon a very rapid Ioffe-trap turn-off time to help distinguish potential antihydrogen signals from cosmic rays.

The newcomers to antihydrogen have big plans. The ASACUSA collaboration hopes to produce antihydrogen within a magnetic trap variation out of which atoms would leak for microwave spectroscopy. Meanwhile, AEGIS proposes interferometry to investigate the gravitational acceleration of 0.1-K antihydrogen atoms if they can be produced.

Everyone doing antihydrogen physics is excited about a possible 100-fold increase in the number of trapped antiprotons that the proposed ELENA upgrade to the AD at CERN would allow. More antihydrogen atoms, more rapid progress, and more precise studies of antihydrogen structure and gravity would certainly result if ELENA angels can be found amongst the funding demons.

Additional resources

- Homepages of the four collaborations hoping to study cold antihydrogen
  ATRAP: http://hussle.harvard.edu/~atrap
  ALPHA: http://alpha.web.cern.ch
  ASACUSA: http://asacusa.web.cern.ch

The online version of this Quick Study provides additional references.
Centrifugal Separation of Antiprotons and Electrons

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Centrifugal separation of antiprotons and electrons is observed, the first such demonstration with particles that cannot be laser cooled or optically imaged. The spatial separation takes place during the electron cooling of trapped antiprotons, the only method available to produce cryogenic antiprotons for precision tests of fundamental symmetries and for cold antihydrogen studies. The centrifugal separation suggests a new approach for isolating low energy antiprotons and for producing a controlled mixture of antiprotons and electrons.

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Centrifuges commonly separate both cells and nuclear isotopes within a fluid rotated at an angular rotation frequency ω. The masses m of the two species are at larger radii because the centrifugal force Fi = mω2r makes it larger than the gravitational force g for larger masses. Simultaneously trapped charged species can similarly separate within a rotating plasma [1]. When antiprotons (p̅) were first cooled via collisions with simultaneously trapped electrons (e−) [2], the electron density, number, and temperature conspired with a high magnetic field to prevent centrifugal separation [3]. Centrifugal separation of much colder, laser-cooled ions was observed when these were used (instead of e−) to cool either another ion species (e.g., [4]) or positrons (e+) [5]. The separated ion distributions were directly imaged using decay photons that followed laser excitation.

Neither lasers nor photon imaging can be used to establish and detect the centrifugal separation of trapped e− and p̅. The predicted separation has not been observed for this basic two-component plasma system. This is surprising given that collisional electron cooling of p̅ [2] is routinely used as the only method to cool p̅ to cryogenic temperatures. (Collisions with any other matter particle would annihilate the p̅.) Electron cooling of p̅ made possible the most stringent test of CPT invariance with a baryon system [6] (a comparison of the charge-to-mass ratios of the p̅ and p) and will be required to realize a 106-fold improved measurement of the p̅ magnetic moment [7]. Electron-cooling is what makes it possible to accumulate trapped p̅ [8] for producing and studying all cold H atoms (e.g., [9,10]), and it enables the production of low energy p̅ beams for collision studies [11].

This Letter reports the observation of centrifugal separation of trapped p̅ and e−. The separation is large and unavoidable for the large electron number (N ∼ 108), large electron density (n ∼ 108 cm−3), and modest magnetic fields (down to B ∼ 1 T) that are currently used along with up to 107 cold p̅ at ATRAP to produce and study slow H. The separation is easily observed with a method that permits gently removing a well-controlled fraction of the cooling e− from a trapped p̅ plasma. The centrifugal separation methods should work just as well with e+ used to cool positive ions since >109 e+ can now be used. (ATRAP accumulates 108 cryogenic e+ at 8 × 105/s for a 20 mCi source, which is 4 × 108 e+ s−1 mCi−1.)

The gold-plated, oxygen-free electrical grade copper trap electrodes used to simultaneously store p̅ and e− [Fig. 1(a)] have a B = 1–3.7 T magnetic field directed along their axis (horizontal in the figure but vertical in reality). The five cylindrical electrodes used to demonstrate separation are part of a stack of nearly 40 electrodes (represented fully in [12]). An 80 eV axial potential well on axis [Fig. 1(b)] is close to a harmonic potential [dot-dashed curve in Fig. 1(b)] when all electrodes are grounded except for 100 V applied to LTE3 [Fig. 1(a)]. The 106 p̅ used for most of the trials reported here are accumulated from 9 pulses of p̅ from CERN’s unique Antiproton Decelerator using trapping and cooling methods [13,14] that are now used for all H experiments. The e− are photoelectrons that are trapped after they are liberated from a metal surface by intense ultraviolet pulses from an excimer laser [15].
including the dashed curve) and deepen off axis (solid curves). Potentials LTE3 produces wells that are nearly harmonic on axis (dotted curve) and vary along the axis is not known. The axial frequency determines the axial oscillation of the length (b) of an electron plasma of \(10^8\) electrons, \(N\) and two measured frequencies (corresponding to the two peaks in Fig. 2). Confirmations of this method were reported earlier [18,19]. The axial frequency \(\omega_z\) is for the plasma’s center-of-mass oscillation along \(\hat{z}\), and the quadrupole frequency \(\omega_2\) is for the oscillation of the length of the \(e^-\) plasma along \(\hat{z}\). The method (e.g., [20]) determines \(\omega_2\) for a spheroidal plasma. Appropriate numerical calculations can extend the method to plasmas that sample regions where the trapping potential deviates significantly from an electrostatic quadrupole [19]. The rotation (and hence the plasma shape and density) continues with the same frequency for hours.

The \(\bar{p}\) might be expected to be a small perturbation on the \(e^-\) plasmas given that the \(\bar{p}\) number is 100 times smaller than the \(e^-\) number. Indeed, the measured radial extent of the electron plasma agrees within measurement uncertainty with what is measured for a plasma with \(10^8\) \(e^-\) and no \(\bar{p}\), suggesting that the shape and density of the \(e^-\) plasma is the same with and without the \(\bar{p}\).

Figure 3 demonstrates centrifugal separation of \(\bar{p}\) and \(e^-\). Figure 3(a) shows that \(e^-\) escape the trap before \(\bar{p}\) as the applied trapping voltage is ramped down. Figure 3(b) shows that a much larger fraction of \(\bar{p}\) than \(e^-\) remain in the trap. The radially centered particles escape first as the applied potential is reduced because the axial potential well is shallowest on the trap’s central axis [Fig. 1(b)]. The separation [Fig. 3(a)] and measured fractions [Fig. 3(b)] do not change when the time over which the trapping depth is reduced is varied between 0.1 and 10 s.

The released \(\bar{p}\) are counted with scintillators that detect \(\bar{p}\) annihilations with 75% efficiency. The released \(e^-\) can only be detected above noise levels when concentrated in small pulses whose charge can be integrated as they strike a conducting plate (biased to suppress the release of secondary \(e^-\)). The “ramps” for Fig. 3(a), and for determining the \(e^-\) remaining for Fig. 3(b), are accordingly a series of 2-V steps separated by time delays.

\[\begin{align*}
\text{(a) Number of } \bar{p} \text{ and } e^- \text{ escaping the trap each time the applied potential is reduced by nonadiabatic, 2-V steps. (b) Fractions of } \bar{p} \text{ and } e^- \text{ remaining after the well depth is ramped adiabatically to the indicated value (with curves to aid the eye). The initial } e^- \text{ plasma has a radius of } 5 \text{ mm in an } 80 \text{ eV well.}
\end{align*}\]
Confirmation of radial separation comes when most of the $10^6 \bar{p}$ and none of the $10^6 e^-$ are lost as $B$ is reduced from 3.7 to 1 T. The reduction expands the radial location of the particles as $B^{-1/2}$ (a consequence of angular momentum conservation) until the $\bar{p}$ annihilate upon striking the electrodes. In the usual symmetric gauge, the conjugate angular momentum for a charge $e$ in a $B$ field is $L_z = (1/2)Be_i(\rho)^2$. It is independent of particle mass and velocity since a negligible mechanical contribution is smaller by the large ratio of the particle’s cyclotron frequency and $\omega_r$.

It is not surprising that electrons are not lost. The sum of angular momenta for $N$ charges $e$ in a spheroid with an outer radius $\rho$ is

$$L_z(\rho) = \frac{1}{2}NeB\rho^2.$$  

$L_z$ conservation thus means a fixed $B\rho^2$. An $e^-$ spheroid prepared with $\rho = 8$ mm (the largest studied) grows to just over 15 mm, well short of the 18 mm electrode radius.

The field at which $\bar{p}$ loss begins as $B$ is reduced (Fig. 4) suggests that the outer $\bar{p}$ radius is much larger than the radius of the electron spheroid. The deduced outer $\bar{p}$ radius decreases when the initial radius of the $e^-$ spheroid is reduced, suggesting that the $\bar{p}$ are not uncoupled from the $e^-$. The superconducting solenoid’s inductance limits the ramp rate to $7 \times 10^{-3}$ T/s, but the result shown does not change if the ramp is slowed by a factor of 2.

A simple estimate establishes when the centrifugal separation of trapped $\bar{p}$ and $e^-$ should take place. Equating the centrifugal energy difference for the two species, $(m_\bar{p} - m_e)\omega^2\rho^2/2$, to $k_BT_{\text{sep}}$ gives the temperature below which separation should be pronounced,

$$T_{\text{sep}} = \frac{m_\bar{p}e^2^2}{8e\rho k_B}\left(\frac{n\rho}{B}\right)^2.$$  

The good approximation $\omega_r = e\rho/(2e_0B) \ll \omega_e$ [20] is used. $T_{\text{sep}}$ ranges from 50 to 100 K for our $e^-$ plasmas with radial extent from 8 to 4 mm and $B = 3.7$ T. The observed separation suggests that the temperature of the $e^-$ plasma within our 1.2 K trap electrodes [21] is below the range given, consistent with direct measurements of the temperature of $\bar{p}$ cooled by the electrons. Comparing to other experiments, the first $e^-$ cooling of $\bar{p}$ [2] used many fewer $e^-$, a lower $e^-$ density, and a higher $B$. The estimated $T_{\text{sep}} = 1$ K [3] is lower than could be realized within 4.2 K trap electrodes so no centrifugal separation was expected. A recent report that there is no centrifugal separation of $\bar{p}$ and $e^-$ is puzzling; it seems inconsistent with the reported plasma temperature and density [22].

The observation of centrifugal separation of $e^-$ and $\bar{p}$ is the first step toward understanding this basic two-component plasma system. What is now needed to understand the system are predictions and measurements of the steady-state spatial distribution of $\bar{p}$.

This $\bar{p}$ distribution within the centrifugally separated plasma is crucial to the removal of $e^-$, and also to the distribution and temperature of the $\bar{p}$ after $e^-$ ejection. The $\bar{p}$ distribution after $e^-$ ejection is important because efficient $\bar{H}$ production requires matching the $\bar{p}$ distribution to the radial $e^+$ distribution. The $\bar{p}$ temperature after $e^-$ ejection is important because cold $\bar{p}$ are a minimal requirement for the production of cold $\bar{H}$.

The same method to remove $e^-$ from the $\bar{p}$ is used as was used when $e^-$ first cooled trapped $\bar{p}$ [2] and in all cold $\bar{H}$ experiments. The depth of a trap that contains $\bar{p}$ and $e^-$ is pulsed to 0 eV with pulses long enough so $e^-$ thermal velocities take them out of the well before the well is restored, but short enough that heavier $\bar{p}$ do not move much or escape. Centrifugal separation of the $\bar{p}$ and $e^-$ should make this pulsed ejection method more effective in that radially centered $e^-$ can leave along the axis without colliding with $\bar{p}$ since these are at larger radii. Fewer pulses, and hence less $\bar{p}$ heating from pulsed electric fields that accelerate them, should be required to get rid of the $e^-$. Conservation of $L_z$ for the $\bar{p}$ makes their initial radial location $\rho_i$ increase when $e^-$ are pulsed out from a centrifugally separated distribution. After the electron ejection, the single component plasma of $\bar{p}$ in an electrostatic quadrupole distribution rearranges into a spheroid with radius $\rho_p$. This spheroid’s angular momentum [from Eq. (1)] is $L_z(\rho_p)$. It equals $L_z$ for the $\bar{p}$ distribution just before the $e^-$ are removed, if their ejection is faster than they can rearrange. When $\bar{p}$ are initially distributed uniformly between $\rho_1$ and $\rho_2$,

$$\rho_1 \leq \rho_i \leq \rho_2 \rightarrow \rho_p = \sqrt{\frac{2}{3}(\rho_1^2 + \rho_2^2)}.$$  

For $\bar{p}$ between a typical $e^-$ spheroid, $\rho_1 = \rho_e = 4.5$ mm, and the $\bar{p}$ outer radius measured for this spheroid, $\rho_2 = 6$ mm, this results in a $\bar{p}$ spheroid with $\rho_p = 8.4$ mm. In the limit that the $\bar{p}$ are initially at the outer boundary of an
electron spheroid at $\rho_e = 4.5$ mm, as might be expected, then $\rho_p = \sqrt{5/2} \rho_e = 7.1$ mm.

This work offers a possible alternative to pulsed ejection of $e^-$. Figure 3(b) illustrates the alternative of removing many $e^-$ without ejection pulses that could accelerate $\tilde{p}$ and raise their temperature. This new approach may allow the $e^-$ removal to be done slowly enough that $e^-$ can cool away some of the $\tilde{p}$ potential energy liberated as $e^-$ are released.

The temperatures of centrifugally separated plasmas before and after one of the component species is removed are interesting and important. The long-term goal [23] of trapping $\tilde{H}$ atoms for precise measurements requires very low temperature $\tilde{p}$ and $e^+$ plasmas. The number of $\tilde{p}$ in the low energy tail of a Boltzmann distribution increases sharply with the distribution temperature, as $T^{-3/2}$. A report on work underway will detail how to use centrifugally separated plasmas to prepare $10^6 \tilde{p}$ with $T < 0.6$ K (without the evaporative loss that gives orders of magnitude fewer $\tilde{p}$ at a comparable temperature [24]).

In conclusion, the centrifugal separation of simultaneously trapped $\tilde{p}$ and $e^-$ is clearly observed and studied. The radial separation is important given that $e^-$ cooling of $\tilde{p}$ is currently the only available method for producing cryogenic $\tilde{p}$. The cooling of $\tilde{p}$ is required for precision tests of fundamental symmetries and for all cold $\tilde{p}$ and $\tilde{H}$ studies. These studies provide some insight into and cautions for the pulse method currently used to separate $\tilde{p}$ from their cooling $e^-$. The technique introduced to demonstrate the centrifugal separation suggests a new approach to remove the cooling $e^-$ with less heating and with good control of the ratio of $\tilde{p}$ to cooling $e^-$. We are grateful to CERN for the 5-MeV $\tilde{p}$ from its Antiproton Decelerator and to T. O’Neil for helpful comments. This work was supported by the NSF and AFOSR of the U.S., the BMBF, DFG, and DAAD of Germany, and the NSERC, CRC, CFI, and OIT of Canada. W. O. was supported in part by CERN.

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Adiabatic Cooling of Antiprotons

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Adiabatic cooling is shown to be a simple and effective method to cool many charged particles in a trap to very low temperatures. Up to $3 \times 10^8 \bar{p}$ are cooled to 3.5 K. This is $10^3$ times more cold $\bar{p}$ and a 3 times lower $\bar{p}$ temperature then previously reported. A second cooling method cools $\bar{p}$ plasmas via the synchrotron radiation of embedded $e^-$ (with many fewer e$^-$ than $\bar{p}$) in preparation for adiabatic cooling. No $\bar{p}$ are lost during either process – a significant advantage for rare particles.

Much energy and effort is required to produce modest numbers of antiprotons ($\bar{p}$) – the stable antimatter nucleus. Reducing $\bar{p}$ energy to form cold antihydrogen ($\bar{H}$) atoms is a big additional challenge. Years of effort have gone towards realizing the original proposal [1] to capture cold $\bar{H}$ atoms in magnetic traps for precise spectroscopy and tests of fundamental symmetries. The latest significant step is an atom confined for a small fraction of a second in 1 of 9 trials [2]. However, greatly improved $\bar{p}$ cooling methods are needed to attain usable numbers of trapped $\bar{p}$ for useful times in known excitation states, and to increase low energy $\bar{p}$ beam luminosity.

Two new cooling methods reported in this Letter together produce the largest cold $\bar{p}$ plasmas – $3 \times 10^8 \bar{p}$ at 3.5 ± 0.7 K. For comparison, evaporative cooling recently reported in this journal [3], yielded $10^4$ times fewer trapped $\bar{p}$ at nearly 3 times the temperature. The central demonstration here is of adiabatic cooling. Also crucial is the embedded $e^-$ cooling that prepares the $\bar{p}$ for adiabatic cooling. Many fewer $e^-$ than $\bar{p}$ are used, just the opposite of the $e^-$ cooling method [4] used to obtain all cold $\bar{p}$ and $\bar{H}$ atoms so far. The number of $e^-$ present during both types of cooling, many fewer than the $e^-$ used to form $\bar{p}$, should be small enough not to inhibit $\bar{p}$ production. Even lower $\bar{p}$ temperatures should be possible with embedded $e^-$ cooling, followed by adiabatic cooling, followed by evaporative cooling.

Adiabatic cooling in a harmonic trap potential takes place when the restoring force $F$ and potential energy well $U$ are reduced while these confine a plasma initially at temperature $T_i$. A measure of $F$ and $U$ is the oscillation frequency $f$ of the plasma’s center-of-mass in the well, since $\omega = 2\pi f$ determines $F = -m\omega^2 z$ and $U = m\omega^2 z^2/2$. Adiabatic cooling takes $T_i$ to $T_f$ as $f_i$ is reduced to $f_f$.

For a low particle density, adiabatic cooling of $\bar{p}$ oscillators [5], implications for the energy analysis of the first trapped [6] and electron-cooled [4] $\bar{p}$, and cooling of hot ions for FTICR [7] have been considered. A particle oscillator’s energy $E$ decreases as its oscillation frequency $f$ is reduced adiabatically because $E/f$ is a familiar adiabatic invariant – the invariant quantized in quantum mechanics. The prediction is thus $T_f = (f_f/f_i) T_i$. If a coupled oscillatory motion contributes heat capacity but no additional cooling (e.g. $\bar{p}$ cyclotron motion) then the individual particle prediction is $T_f = (f_f/f_i)^{3/2} T_i$.

The density of the plasmas for this demonstration is high enough to make the Debye length smaller than the plasma size. The plasmas are weakly correlated, with a kinetic energy larger than the Coulomb repulsion energy between neighboring $\bar{p}$ on average. The $\bar{p}$ within the plasma thus move and collide within the plasma boundary approximately as an ideal gas (viewed in the appropriate rotating reference frame [8]). The prediction for an ideal gas [8, 9] is

$$T_f = (V_i/V_f)^{2/3} T_i. \quad (1)$$

Adiabatic cooling takes place when the restoring force does negative work on the plasma to increase its volume $V$ and decrease its temperature $T$, all with no entropy change.

The adiabatic condition for low $\bar{p}$ density is that $f$ changes very little during an oscillation period, $\dot{f}/f \ll f$. For a dense $\bar{p}$ plasma, a plasma has been changed adiabatically and reversibly if its final temperature $T_f$ is independent of the rate at which $f$ is changed. For all densities, the adiabatic cooling and the measurement of $T_f$ must take place before any other process changes the plasma temperature (e.g. embedded $e^-$ cooling).

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The \( N_p = 2 \times 10^5 \) to \( 3 \times 10^8 \) \( \text{e}^- \) used for the trials reported here are accumulated from 1 to 21 injection pulses of \( \text{e}^- \) from CERN’s unique Antiproton Decelerator. The trapping [6], electron-cooling [4] and stacking [10] methods that have accumulated up to \( 1.1 \times 10^7 \) \( \text{e}^- \) at ATRAP are those employed for all \( \text{e}^- \) experiments [11]. The \( \text{e}^- \) are farther from the trap axis. The adiabatic cooling is slow with a large number of surrounding \( \text{e}^- \). Typically \( N_e = 10^8 \) photoelectrons are used after they are liberated from a metal surface by intense ultraviolet pulses from an excimer laser [12]. A “rotating wall” drive [13] compresses a spheroidal \( \text{e}^- \) plasma to a 2 mm radius, and the plasma cools via \( \text{e}^- \) synchrotron radiation. After \( \text{e}^- \) are loaded they cool via collisions with the cold \( \text{e}^- \). Centrifugal forces on the simultaneously rotating \( \text{e}^- \) plasmas separate them radially [14] so the \( \text{e}^- \) are farther from the trap axis.

Directly manipulating trapped \( \text{e}^- \), measuring their temperature, and using them for experiments is difficult if \( N_e \gg N_p \), as in standard \( \text{e}^- \) cooling. \( \text{e}^- \) production, for example, would be inhibited if \( \text{e}^- \) substitute for \( e^+ \) in what would otherwise be the replacement collisions [15] that form more deeply bound \( \text{e}^- \) atoms. The inverted situation for embedded \( e^- \) cooling, with \( N_p \gg N_e \) and each \( e^- \) surrounded by many \( \text{e}^- \), cools \( \text{e}^- \) much more slowly but no less effectively. To investigate embedded \( e^- \) cooling, most of the \( e^- \) are ejected along the trap’s center axis using a method introduced along with \( e^- \) cooling [4]. The depth of the trap containing the \( \text{e}^- \) and \( e^- \) is pulsed to 0 eV. The pulses are long enough that \( e^- \) thermal velocities can take them out of the well before the well is restored, but short enough that the heavier \( \text{e}^- \) cannot escape. Three or four pulses leave all of the \( \text{e}^- \) in the trap, along with \( N_e = 6 \times 10^6 \) or \( 9 \times 10^6 \) \( e^- \) (estimated from observed heating rates below). After the ejection raises the \( \text{e}^- \) temperature to typically hundreds of K, embedded \( e^- \) cooling cools the \( \text{e}^- \) by an order of magnitude in temperature.

The \( \text{e}^- \) and remaining \( e^- \) are confined in a potential well made by biasing gold-plated, copper ring electrodes (Fig. 1a) with a \( B = 3.7 \) T field along their symmetry axis. The electrodes shown are part of a stack of 39 electrodes (represented fully in [16]). The potential applied to electrode LTE2 in Fig. 1a determines the empty-trap well depth \( W_0 \) (eg. Figs. 1b-c), and also the small-amplitude oscillation frequency \( f \) for a single \( \text{e}^- \) in the otherwise empty well. (Thus \( f \) characterizes an empty well rather than being defined as an oscillation frequency of a trapped plasma.) Plasma space charge reduces the energy required for a \( \text{e}^- \) to escape the plasma and trap (along the \( z \)-axis) to \( W \leq W_0 \) (Fig. 1c). The dependence of \( W \) on \( W_0 \) and \( f \), along with \( N_p \) and plasma geometry, is calculated with finite difference methods [17].

The small number of \( e^- \) embedded within the \( \text{e}^- \) cool or heat the plasma to a temperature \( T_i \). This steady-state \( T_i \) is determined by blackbody radiation from the trap electrodes and by electrical noise that drives the particles directly. The time scale for embedded \( \text{e}^- \) cooling is that required to cool \( N_p \) antiprotons via the synchrotron radiation of \( N_e \) electrons, each at a rate \( \gamma_c = 4r_0\omega_e^2/3c = (0.2 \text{ s}^{-1}) \). (Here \( r_0 \) is the classical electron radius, \( \omega_e \) is the \( e^- \) cyclotron frequency, and \( c \) is the speed of light.) On average, a \( \text{e}^- \) in the plasma thus cools at the rate \( \gamma_p = \gamma_c N_e/N_p \). The assumption that the energy of the \( \text{e}^- \) is transferred to the \( e^- \) via collisions at a rate \( \gamma_{ep} \), justified below, is possible since \( \gamma_p^{-1} \geq 17 \text{ s} \) for our trills. The coupled rate equations that describe the \( \text{e}^- \) and \( e^- \) temperatures [5] simplify to equal \( \text{e}^- \) and \( e^- \) temperatures, \( T \), with \( dT/dt = -\gamma_p (T - T_i) \). For times \( t \gg \gamma_p^{-1} \), the \( \text{e}^- \) and \( e^- \) share the steady-state temperature, \( T_i \). Adiabatic cooling to \( T < T_i \) is observed if cooling is complete and \( T \) measured in time \( t \ll \gamma_p^{-1} \).

Collision rates within the plasma are fast compared to \( \gamma_p \). For \( B = 0 \), a classic treatment [18] gives \( \gamma_p \) - \( e^- \) collision rate \( 10^8 \) times larger than \( \gamma_p \) for our plasmas. The rate for collisions that couple radial and axial energy is suppressed when a strong \( B \) is added along the trap axis [19]. Even with the predicted suppression by a factor of \( 10^8 \), the axial-radial collision rate is much faster than \( \gamma_p \), with a time constant shorter than \( 0.01 \text{ s} \) for even our lowest temperatures. Since the biggest effect of \( B \) is to inhibit the axial-radial coupling, we assume that the \( \text{e}^- \) - \( e^- \) collision rate \( \gamma_{ep} \) is also larger than \( \gamma_p \) by at least \( 3 \) orders of magnitude.

Adiabatic cooling starts with an initial \( f_i \) chosen to be between 3 MHz and 90 kHz, corresponding to \( W_0 \) between 800 and 0.4 eV on axis. The initial \( f_i \) is lowered to \( f_f \), the latter corresponding to a well depth \( W \) just big enough to keep \( \text{e}^- \) from escaping. The adiabatic cooling is completed in hundreds of ms, with the cooling result the same when this time is varied by a factor of \( 5 \). The cooling time is short compared to \( \gamma_p^{-1} \), so that embedded \( e^- \) cooling has negligible effect during adiabatic cooling.

The \( \text{e}^- \) plasma temperature after adiabatic cooling is revealed [20] by the first few thousand \( \text{e}^- \) that escape (too few to modify \( T \)) as \( W_0 \) is reduced linearly at \( 2.2 \text{ eV/s} \) to the value at which \( \text{e}^- \) escape, at a \( W_0 \) that corresponds to \( f_f \). Thermal energy allows the initial \( \text{e}^- \) to escape over the

![FIG. 1. (a) Cross section of trap electrodes with the location of the \( \text{e}^- \) plasma. (b) On-axis potential energies for \( \text{e}^- \) from escaping. The adiabatic cooling is complete and \( \gamma_p \) is transferred to the \( e^- \) via collisions at a rate \( \gamma_{ep} \). (c) Expanded view without (solid curve) and with (dashed curve) the space charge potential energy for \( N_p = 5 \times 10^5 \).](image-url)
potential barrier, along z to the left in Figs. 1b-c. Over the range of the plasma temperatures in this report, $f_f$ (determined mostly by space charge) varies by $\pm 2\%$. The number escaping, $dN_p$, for a series of small reductions in the empty trap well depth, $dW_0$, is counted as a function of $W_0$. Surrounding scintillators detect $\Xi$ annihilations with a 75% efficiency. Each $\Xi$ loss spectrum in Fig. 2a shows the first antiprotons escaping as a sharp edge to the right (expanded examples in Fig. 2b). The edges are at larger $W_0$ for larger $N_p$. Variations of about 10 meV, from variations in $N_p$ and the plasma radius, are small and do not change the slope of the edges. For a Boltzmann distribution, $\ln(dN_p/dV) \propto -W/kT$. The conversion between $W$ and $W_0$ used to convert the measured $dN_p/dW_0$ comes from the finite difference calculations. If space charge is neglected (i.e. $W = W_0$ assumed), the incorrectly deduced $T$ for $N_p = 5 \times 10^5$ would typically be 1.3 to 2 times larger, the latter for the lowest temperatures.

Adiabatic cooling produces the lowest $\Xi$ temperatures directly measured, $T = 3.5 \pm 0.7$ K (the gray band of Fig. 3 for $f_i > 400$ kHz). Before leveling off at this value, the measured $T$ fits to a power law in $f_i$ for the well within which embedded $e^{-}$ establish initial equilibrium at $T_i = 31$ K. (A noise drive applied to a nearby electrode increases $T_i$ to this easily observed value from what otherwise would be 17 K.) The frequency $f_i$ describes the well from which $\Xi$ begins to escape. The uncertainties on the points indicate measurement reproducibility.

What prevents observed temperatures that are even lower is not yet understood. One possibility is that the source of such a limit has yet been identified. A second possibility is that some technical noise keeps the $\Xi$ from reaching a lower $T$, but the source of such noise has not yet been found. A third possibility is that the better theoretical understanding needed for adiabatic cooling will reveal a slope change at $f_i \approx 400$ kHz in Fig. 3.

The cooling in Fig. 3 is more effective than predicted for small $f_f/f_i$. The ideal gas prediction uses Eq. 1 with plasma volumes from the finite difference calculations for realistic trap potentials. The prediction does not change noticeably when the volumes are approximated as spheroids [21] (the required plasma shape within an electrostatic quadrupole potential). Of course, the $\Xi$ plasma is not an ideal gas of constant density within sharply defined boundaries. The density actually drops off over a temperature-dependent Debye length that has yet to be included in the theoretical description. Also compared in Fig. 3 are predictions $T \propto f_i^{-1}$ and $T \propto f_i^{-1/2}$ from the familiar adiabatic invariant of an oscillator.

An important feature of adiabatic cooling is that no particle loss is observed. This makes it possible to cool large numbers of $\Xi$. This is important for low energy $\Xi$ experiments given that $\Xi$ are not readily available. For example, the long term goal of trapping $\Xi$ atoms for precise laser spectroscopic comparisons to hydrogen atoms [1] requires as many cold atoms with energies below 0.5 K as possible. This energy is the depth of the deepest magnetic traps for $\Xi$ atoms that can be constructed with state-of-the-art superconducting technology. Larger numbers of colder $\Xi$ would seem to be a necessary (though not sufficient) step towards useful numbers of trapped $\Xi$ atoms.

Figure 4 illustrates the slow return to equilibrium at $T_i$ after adiabatic cooling. The rate $\gamma_p$ is faster with more $e^{-}$ (after 3 rather than 4 ejection pulses). An exponential fit determines $N_e$ in terms of the separately measured $N_p$ since $\gamma_p = \gamma_e N_e/N_p$. Both curves in Fig. 4 rise to the same $T_i$, suggesting that $e^{-}$ rather than $\Xi$ are being heated to make $T_i > 1.2$ K (the electrode temperature [22]). A consistent $\gamma_p$ can be similarly and independently determined from the $T$ measured as $\Xi$ cool to $T_i$.  

FIG. 2. (a) Superposition of $\Xi$ loss spectra for indicated $N_p$ as $W_0$ is reduced linearly in time (i.e. right to left). (b) $T$ is determined from the exponential slope of the first thousand $\Xi$ to escape as $W_0$ is reduced. The three examples are aligned so the slopes can be readily compared.

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FIG. 3. Measured and predicted temperatures for $5 \times 10^5$ $\Xi$ after adiabatic cooling. The measured $T$ fits a power law (solid curve) down to the lowest $T$ measured (gray band).
FIG. 4. After adiabatic cooling of $5 \times 10^7 \overline{\Xi}$, thermal equilibrium at $T_i$ is slowly reestablished at a rate $\gamma_{\Xi}$ that increases with $N_\Xi$. The $T = 2.5 \text{ K}$ at the left is consistent with best-fit of the measured $T$ in Fig. 3.

The embedded $e^{-}$ cooling of $\overline{\Xi}$ that establishes $T_i = 17 \text{ K}$ is also important on its own, e.g. to remove heat added when particles are moved to new locations. Reducing noise that heats the $e^{-}$ (perhaps from radio or TV stations, or from the many electrical signals in the decelerator hall) should make $T_i$ approach the 1.2 K electrode temperature, and an even lower $T$ after subsequent adiabatic cooling.

Finally, adiabatic cooling is naturally compatible with producing $\overline{\Theta}$ that can be trapped insofar as the $\overline{\Xi}$ rotation velocities are low in the shallow well at the conclusion of the cooling. $\overline{\Theta}$ formed with such velocities could be captured a magnetic trap.

In conclusion, adiabatic cooling is shown to be an effective method for cooling far more $\overline{\Xi}$ than have previously been cooled. The $\overline{\Xi}$ are cooled to $T = 3.5 \pm 0.7$, the lowest directly measured $\overline{\Xi}$ temperature. Adiabatic cooling thus promises to be an important method for attain usable numbers of $\overline{\Theta}$ atoms that are cold enough to be confined in a magnetic trap. The $\overline{\Xi}$ are prepared for adiabatic cooling using embedded electron cooling. This cooling method, shown to cool many $\overline{\Xi}$ with much fewer $e^{-}$, has some promise on its own. Orders of magnitude more cold $\overline{\Xi}$ are produced by embedded electron cooling followed by adiabatic cooling than by evaporative cooling, in part because the latter requires significant particle loss. Embedded electron cooling, followed by adiabatic cooling, followed by evaporative cooling should give much lower $\overline{\Xi}$ temperatures.

We are grateful to CERN for the 5-MeV $\overline{\Xi}$ from its Antiproton Decelerator. This work was supported by the NSF and AFOSR of the US, the BMBF, DFG, and DAAD of Germany, and the NSERC, CRC, CFI and ERA of Canada. W.O. is supported in part by CERN.

Self-Excitation and Feedback Cooling of an Isolated Proton

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The first one-proton self-excited oscillator (SEO) and one-proton feedback cooling are demonstrated. In a Penning trap with a large magnetic gradient, the SEO frequency is resolved to the high precision needed to detect a one-proton spin flip. This is after undamped magnetron motion is sideband cooled to a 14 mK theoretical limit, and despite random frequency shifts (typically larger than those from a spin flip) that take place every time sideband cooling is applied. The observations open a possible path towards a million-fold improved comparison of the $\hat{p}$ and $p$ magnetic moments.

A single proton is suspended in a vertical $B = 5.68$ T field at the center of a cylindrically symmetric trap (Fig. 1)—stacked rings with a 3 mm inner radius. The electrodes and surrounding vacuum container are cooled to 4.2 K by a thermal connection to liquid helium. Cryopumping of the closed system made the vacuum better than $5 \times 10^{-17}$ Torr in a similar system [16], so collisions are not important. Appropriate potentials applied to copper electrodes (with an evaporated gold layer) in an open-access geometry [17] make a very good electrostatic quadrupole near the trap center, while also maintaining an open access to the trap interior from either end.

The proton’s circular cyclotron motion is perpendicular to $B$, with a frequency $\omega_{c}/(2\pi) = 79.5$ MHz that is slightly modified by the electrostatic potential. The proton also oscillates parallel to $B$ at $\omega_{z}/(2\pi) = 553$ kHz. Because the potential is not a perfect quadrupole, this frequency depends slightly upon oscillation amplitude $A$ with $\omega_{z}(A) = \omega_{z}$. The proton’s third motion is a circular magnetron motion, also perpendicular to $B$, at the much lower frequency, $\omega_{\omega}/(2\pi) = 1.9$ kHz.

To couple the proton spin moment and the magnetron state that is the outcome of sideband cooling to the measurable $\omega_{z}(A)$, the trap’s central ring electrode is made of saturated iron (unlike the copper endcap and compensation...
electrodes above and below). The extremely large magnetic bottle gradient,

$$\Delta B = \beta_2 [(z^2 - \rho^2/2) \hat{z} - z \rho \hat{\rho}],$$  \hspace{1cm} (1)

with $\beta_2 = 7.8 \times 10^4$ T/m$^2$, is 51 and 8 times larger than what was used to measure free [3] and bound [5,14] electron magnetic moments. The bottle reduces the field within the trap by 0.47 T (8%).

The axial frequency $\omega_z(A)$ depends primarily on the strength of the $z^2$ term in the electrostatic quadrupole. A magnetic moment $\mu \hat{z}$ (from circular cyclotron or magnetron motions, or from spin) adds a term going as $\mu z^2$ to the trapping potential, shifting $\omega_z(A)$ by

$$\Delta \omega_z = \frac{h \beta_2}{2m_p \omega_z} B \left[ n + \frac{1}{2} + \frac{g_p m_s}{2} + \frac{\omega_z}{\omega_A} \right],$$  \hspace{1cm} (2)

The magnetic moments from cyclotron and magnetron motion go as $n$ and $\ell$. The 553 kHz axial frequency shifts by 21 mHz per cyclotron quantum (200 Hz per $\mu$m for our typical cyclotron radius), and by 0.5 $\mu$Hz per magnetron quantum (40 mHz per $\mu$m at our typical magnetron radius). A proton spin flip will cause a 60 mHz shift.

The frequency of the current induced to flow through $R$ in Fig. 1 by the axial oscillation is measured to determine $\omega_z(A)$. The voltage across $R = 25$ M$\Omega$ is Fourier transformed after an amplifier that uses a high electron mobility transistor (HEMT) with good thermal connection to 4.2 K. The $I^2R$ loss for the induced current going through $R$ gives an axial damping time $\gamma_z^{-1} = 60$ ms.

$R$ represents losses in an LC tuned circuit resonant at $\omega_z$. The losses are minimized to maximize $R$, the observed signal and the damping rate. Varactors tune the circuit and its matching to the HEMT. A superconducting inductor with $L = 2.5$ mH cancels the reactance of the trap capacitance, leaving $R = Q \omega_z L$. The circuit’s quality factor is tuned to $Q = 3000$ with the trap electrodes attached, recently improved to $Q = 7500$. The proton’s cyclotron and magnetron motions in this trap are not damped.

A nearly identical “precision trap” is just below the trap in Fig. 1. A detection circuit resonant at $\omega_c / (2\pi) = 86.5$ MHz, attached across halves of a copper ring electrode, damps this motion in $\gamma_c^{-1} = 10$ min. (This could be 3 times faster with better amplifier tuning.) An axial amplifier detects and damps the axial motion.

A single proton is isolated in the second trap using a relativistic method we developed earlier with antiprotons [18]. An H atom is ionized in the trap by an $e^-$ beam from a sharp field emission point. Strong driving forces applied at the axial frequencies of unwanted ions keep them from loading. A strong pulse of cyclotron drive produces one-proton cyclotron resonances that differ in frequency because of differing cyclotron energies and relativistic mass shifts of $\omega_z$. The trap potential is temporarily reduced until the signal from only one proton remains. The cyclotron energy of the remaining proton damps until its radius is less than 0.5 $\mu$m average for a 4.2 K distribution. After magnetron cooling, the proton is transferred into the trap of Fig. 1 by adjusting applied potentials to make an axial potential well that moves adiabatically from the lower to the upper trap.

The proton axial oscillation whose frequency is to be measured satisfies the equation of motion,

$$\ddot{z} + \gamma_z \dot{z} + [\omega_z(A) + \Delta \omega_z]z = F_d(t)/m.$$  \hspace{1cm} (3)

A driving force $F_d(t)$ is added to the restoring force (from the electrostatic quadrupole and the magnetic bottle), and to the damping force $-m \gamma_z \dot{z}$ (from the loss in $R$).

With no feedback, $F_d$ is the Johnson noise from the resistor that is then amplified and detected. The proton’s axial oscillation shorts this noise [19], making a dip in the noise power spectrum [Fig. 2(b)] whose half width is $\gamma_z$.

The axial frequency is determined to higher precision using the better signal-to-noise and narrower signal width of a one-proton SEO [Fig. 2(a)]. The one-particle SEO, realized previously only with an electron [1], is realized by adjusting the amplitude and phase of the amplified induced signal and feeding this back to the other side of the trap as a driving force on the proton. The feedback produces a force $F_d(t) \sim mG \gamma_z \dot{z}$ with feedback gain $G$. Self-excitation occurs, in principle, when the feedback cancels the damping at $G = 1$. Noise causes amplitude diffusion and energy growth, however, and $G$ slightly different from unity will either decrease or increase $A$ exponentially. A stable and useful SEO thus requires limiting the amplitude to some value $A_0$. Here a digital signal processor chip Fourier transforms the signal to determine $A$, and makes $G = 1 + a(A - A_0)$ [1].

An axial oscillation $z(t) = A \cos(\omega t)$ generates a feedback force $F_d(t) = -\omega A G m \gamma_z \sin(\omega t + \phi)$, when a phase shift $\phi$ is introduced (Fig. 1). Inserting in Eq. (3) yields

$$G \cos(\phi) = 1,$$  \hspace{1cm} (4)

FIG. 2 (color). SEO peak (a) and noise dip (b) for 160 s of averaging. (c) Frequency resolution achieved with a single average of an SEO peak (black $x$) and noise dip (red $x$), with the standard deviation (black points) and Allan deviation (black triangles) of averaged SEO measurements. (d) Drift of 256 s averages over 16 nighttime hours.
For $(\gamma_z/\omega_z) \tan(\phi) \ll 1$, the SEO thus depends on $\phi$ as
\[ \omega(A, \phi) = \omega_z(A) + \frac{\gamma_z}{2} \tan(\phi). \] 

With positive feedback, and a feedback phase adjusted to optimize the signal [Fig. 3(a)], the measured SEO frequency as a function of feedback phase fits well to Eq. (6) [Fig. 3(b)]. The scatter in repeated frequency measurements [Fig. 3(c)] is reduced when the trapping potential is tuned to make the best possible electrostatic quadrupole.

Sideband cooling, a method to radially center the proton, is especially important given that the magnetic field changes significantly as a function of radial position. A sideband cooling drive at $\omega_z + \omega_+/2$ magnifies and produces a measurably different magnetron state and $\omega_z(A)$, so the sequence is repeated to make histograms of measured axial frequencies.

The gray histogram and Gaussian fit in Fig. 4(a) show the scatter for repeated measurements of $\omega_z(A)$ taken with no sideband cooling drive (i.e., no change in magnetron radius) and no feedback (i.e., no change in $T_z$). Sideband cooling with no feedback broadens the gray into the green histogram [Fig. 4(a)]. A convolution (green curve) of Eq. (10) with $T_m = 30 \text{ mK}$ (corresponding to $T_z = 8 \pm 2 \text{ K}$) and the gray Gaussian resolution function fits the measured histogram when Eq. (2) is used to convert magnetron energy to axial frequency shift.

The outcome of sideband cooling is investigated with a three-step sequence. First, the axial energy is left in equilibrium with the detection resistor or modified using feedback. Second, a sideband cooling drive at $\omega_z + \omega_+$ is applied and then turned off. Third, the SEO is started and $\omega_z(A)$ measured. Each application of sideband cooling produces a measurably different magnetron state and $\omega_z(A)$, so the sequence is repeated to make histograms of measured axial frequencies.

The scatter for repeated measurements of $\omega_z(A)$ taken with no sideband cooling drive (i.e., no change in magnetron radius) and no feedback (i.e., no change in $T_z$). Sideband cooling with no feedback broadens the gray into the green histogram [Fig. 4(a)]. A convolution (green curve) of Eq. (10) with $T_m = 30 \text{ mK}$ (corresponding to $T_z = 8 \pm 2 \text{ K}$) and the gray Gaussian resolution function fits the measured histogram when Eq. (2) is used to convert magnetron energy to axial frequency shift.

The axial temperature is reasonably higher than the $T_z = 5.2 \text{ K}$ we realized with one electron in a 1.6 K apparatus [2].

Feedback changes the measured $T_z$ as predicted, from $T_{z0}$ at $G = 0$ to $T_z(G) = (1 - G)T_{z0}$ [Fig. 5(b)], increasing our confidence in this new way to determine a low $T_z$. The damping widths also change as predicted, from $\Gamma_{z0} = (1 - G)\Gamma_{z0}$ [Fig. 5(a)]. The ratios in Fig. 5(c) are constant, consistent with the fluctuation-dissipation theorem. Feedback cooling to $T_z = 4 \text{ K}$ narrows the distribution of magnetron states [blue histogram in Fig. 4(a)] such that the effective magnetron temperature is $T_m = 14 \text{ mK}$. Feedback cooling from $T_z = 8$ to 4 K seems plausibly higher than the 5.2 to 0.85 K [2] achieved in a 1.6 K apparatus. Feedback heating to $T_z = 20 \text{ K}$ broadens the distribution [red histogram in Fig. 4(a)].

A check on the magnetron orbit size produced by sideband cooling comes from expanding the orbit size exponentially with a sideband heating drive at $\omega_z - \omega_+$ [7,13].

![FIG. 4 (color). (a) Histograms of magnetron states after no sideband cooling (gray), and produced by sideband cooling using feedback cooling (blue), no feedback (green), and with feedback heating (red). Solid curves are convolutions of the gray Gaussian resolution function and Boltzmann distributions at the specified $T_z$. (b) The magnetron radius increase from a sideband cooling drive at $\omega_z + \omega_+$ is fit to an exponential and extrapolated back to an initial magnetron radius.](143001-3)
Each trial [e.g., Fig. 4(b)] is extrapolated to determine the radius at the start of the heating. Averaging the initial radii from 200 trials gives 11 ± 2 μm, consistent with $T_z = 8 ± 2$ K from Fig. 4(a), and hence with the theoretical cooling limit [Eq. (11)]. We do not understand the earlier electron observations [7,13] but note that progress has been made in the detection electronics that sets $T_z$.

For the first time in a strong magnetic gradient, the resolution achieved in measuring $\omega_z(A)$ is comparable to the 60 mHz needed to observe a proton spin flip [for an averaging time greater than 16 s in Fig. 2(c)]. The resolution is much better for a SEO measurement (black x) than for a dip measurement (red x). Repeated SEO frequency measurements have a standard deviation (black points) and for a single measurement. Fluctuations in the trapping potential, mechanical vibrations, temperature variations, and fluctuating contact potentials are being investigated as possible sources of the scatter.

Sideband cooling is required to minimize the scatter and achieve the 60 mHz resolution. However, sideband cooling randomly selects a new magnetron radius, typically shifting $\omega_z$ by more than 60 mHz. A solution starts with an initial sideband cooling period, after which $\omega_z$ is measured. An attempt to make a spin flip can be then made for several minutes, during which time unwanted magnetron heating shifts $\omega_z$ typically by about 0.3 Hz/h [Fig. 2(d)]. Measuring $\omega_z$ will thus reveal a shift larger or smaller than 60 mHz depending upon whether the spin has or has not flipped. These steps can then be repeated.

In conclusion, a one-proton self-excited oscillator and one-proton feedback cooling are realized for the first time. A very strong magnetic gradient is added to the Penning trap in which the proton is suspended to make it possible to observe sideband cooling distributions and to investigate the possibility of observing spin flips. Sideband cooling of the undamped proton magnetron motion to 14 mK is demonstrated, even though every application of sideband cooling shifts the monitored SEO oscillation frequency more than would a spin flip. As an application, the SEO oscillation frequency is resolved at the high precision needed to observe a spin flip of a single $\bar{p}$ or $p$, opening a possible new path towards comparing the $\bar{p}$ and $p$ magnetic moments at a precision higher than current comparisons by 6 orders of magnitude or more.

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Lone Proton

A small test mass attached to a spring and driven to oscillate will furnish information on the mechanical properties of the spring itself and also the medium in which it is immersed. In a similar fashion, probing the oscillation frequency of a single trapped electron provides knowledge of the magnetic moment of the electron (the test mass) as well as a precise knowledge of its electromagnetic environment by way of the fine structure constant. As matter is made up of electrons, protons, and neutrons, it seems natural to ask how the magnetic properties of all the elementary particles arise. However, because the magnetic properties of nucleons are much weaker than those of electrons, correspondingly precise measurements become very challenging. Hoping to change that situation, Guise et al. have developed a technique to trap and probe a single proton (or antiproton). The asymmetries between matter and antimatter can also be addressed in this context at the fundamental level. — ISO

Abstract

Extremely precise tests of fundamental particle symmetries should be possible via laser spectroscopy of trapped anti-hydrogen (H) atoms. H atoms that can be trapped must have an energy in temperature units that is below 0.5 K – the energy depth (in temperature units) of the deepest magnetic traps that can currently be constructed with high currents and superconducting technology. The number of atoms in a Boltzmann distribution with energies lower than this trap depth depends sharply upon the temperature of the thermal distribution. For example, ten times more atoms with energies low enough to be trapped are in thermal distribution at a temperature of 1.2 K than for a temperature of 4.2 K. To date, H atoms have only been produced within traps whose electrode temperature is 4.2 K or higher. A lower temperature apparatus is desirable if usable numbers of atoms that can be trapped are to eventually be produced. This report is about the pumped helium apparatus that cooled the trap electrodes of an H apparatus to 1.2 K for the first time. Significant apparatus challenges include the need to cool a 0.8 m stack of 37 trap electrodes separated by only a mm from the substantial mass of 4.2 K Ioffe trap and the substantial mass of 4.2 K solenoid. Access to the interior of the cold electrodes must be maintained for for antiprotons, positrons, electrons and lasers.

Keywords: liquid helium, refrigerator, Penning trap, antiproton, antihydrogen

1. Introduction

A long term goal of antihydrogen studies is to trap antihydrogen atoms for precise laser or microwave spectroscopy that will probe for any tiny differences between hydrogen and antihydrogen atoms [1]. A neutral atom trap offers the most efficient use of what will always be a limited number of antimatter atoms. A significant challenge is that only atoms with an energy less than about $k_B(0.5 \text{ K})$ can be trapped in the deepest magnetic traps that can be built to confine antihydrogen atoms. The plasmas of positrons and electrons that have been used for antihydrogen production so far were produced within traps with electrodes at 4.2 K [2, 3] and higher [4]. Presumably antiprotons that cool by collisions with these plasmas reach a similar temperature or can be made to do so, though methods to directly measure the temperatures of electrons, positrons and antiprotons are still being developed. (Cooling via resonant couplings to cold circuits is not practical for the number of particles, electrodes, and electrode potentials that must be used.)

The number of H atoms with an energy less than a 0.5 K trap depth increases sharply as the temperature of a H atom distribution is reduced. Relevant to this work is that about ten time more H atoms could be trapped from a 1.2 K thermal distribution than from a 4.2 K distribution. A necessary condition for producing lower temperature atom distribution are antiprotons and positrons with lower energies, and this in turn will typically require lower temperature trap electrodes as a necessary (but not
sufficient) condition.

Trap electrodes colder than 4.2 K have been produced previously only for small electron traps with dimensions on order of 1 cm. The first realization utilized a dilution refrigerator to cool cylindrical trap electrodes to below 100 mK. Quantum transitions between the lowest cyclotron states of a single suspended electron were observed and used to establish that the electron cyclotron motion came into thermal equilibrium with the 100 mK trap electrodes [5], and then later to measure the electron magnetic moment to 3 parts in $10^{13}$ [6, 7]. A later attempt to adapt these methods to trapping an electron in a planar Penning trap for quantum information studies realized a similar electrode temperature [8].

Cooling trap electrodes within an antihydrogen apparatus is much more challenging than cooling a small electron trap. An H apparatus also presents challenges that are not generally present for more familiar pumped helium configurations [9–11]. First, the ATRAP Penning trap electrodes to be cooled are a 0.8 m long stack of 37 gold-plated copper ring electrodes separated by MACOR insulators (Fig. 1). The thermal paths to these electrodes are thus through long electrical leads and through insulating spacers. Second, the electrodes to be cooled to 1.2 K are located within a 4.2 K superconducting solenoid at one end, and extend 0.4 m into the bore of a 4.2 K superconducting Ioffe trap at the other (Fig. 1), both of which must be anchored at 4.2 K to allow up to 90 amps of current to flow within a centimeter of the electrodes. Third, no magnetic materials that would distort the fields of the Penning or Ioffe traps can be used. Fourth, access to the cold electrodes for antiprotons, positrons, electrons and lasers must be maintained. Fifth, uninterrupted operation over many months must be possible since the apparatus must function reliably during the six months per year that CERN provides scheduled daily shifts of antiprotons. Sixth, it is desirable that the system is compatible with a later upgrade to a pumped $^3$He or a dilution refrigerator system if this becomes necessary.

The low temperature apparatus is described in Sec. 2. The cool-down and operation of the refrigeration system is described in Sec. 3, along with two different modes of operation. The design and characterization of the cooling power (Sec. 4), the heat load (Sec. 5) and the helium conductance rate (Sec. 6) are discussed, as is the method for coupling the electrodes to the refrigeration system (Sec. 7). Since this type of refrigeration system has not been previously been used for particle trapping and H studies, the basic low temperature physics and parameters needed to design such a system are summarized.

To illustrate the potential usefulness of the apparatus and methods reported here, we append in Sec. 8 a brief demonstration of the possibility to form low temperature plasmas of electrons and positrons within the 1.2 K system. By measuring the oscillation frequency of the center-of-mass of a plasma suspended within a Penning trap, and also the frequency of an internal oscillation mode of the

![Figure 1: Cylindrical ring electrodes are cooled to 1.2 K while surrounded and mechanically supported by a 4.2 K Ioffe trap apparatus from above, and surrounded by a 4.2 K solenoid. Within a vertically directed 1 T bias field from an external solenoid (not shown), the 1.2 K electrodes are biased to form Penning traps for $\bar{p}$, $e^+$ and $e^-$. A refrigerator-cooled shield (not shown) encloses this apparatus.](image)
trapped plasma, we can deduce the density and shape of the trapped single-component plasma [12]. Shifts in these frequencies indicate changes in plasma temperature [13]. For a spherical plasma we observe that increasing the 1.2 K temperature of the electrodes by 3 K increases the measured plasma temperature by the same amount.

Finally, the possibility of attaining lower temperature electrodes is evaluated in light of what has been learned, in Sec. 9.

2. The 1.2 K Apparatus

The principle components of the modular 1.2 K system (Fig. 2) are made of nonmagnetic materials. OFE copper is used where this is mechanically possible to improve the thermal conductivity. Modular vacuum connections are made using 34 mm diameter, mini conflat flanges made of commercially pure grade 2 titanium. Superleak tight joints between titanium and copper are made by hydrogen brazing 99.95% silver adapters to OFE copper and electron beam welding the silver adapter to a titanium conflat flange.

Liquid helium from a large 4.2 K reservoir is filtered through a 5 µm pure silver filter paper (Sterlitech) to prevent the entry of particle impurities that could clog the capillaries that follow. The filtered helium goes through a home built needle valve that can be adjusted by turning a G-10 tube that extends outside the cryogenic system. The titanium needle has 1.4 threads/mm (36 threads/in) and a 7° taper to allow fine adjustments of the helium impedance and flow. The silver valve body is welded between two titanium conflat flanges using an electron beam. The design requirement to use only nonmagnetic materials led to an unusual design for the needle valve, such that it is a good thermal short along its length. Usually these valves are made of a soft metal such as brass with a stainless steel needle and flanges. To avoid magnetic field distortions nominally nonmagnetic ferrous alloys are not used. Instead, titanium is used for the needle and flanges. Since this could not be easily joined to brass we made the valve seat from pure silver that was electron-beam welded into titanium mini conflat flanges.

The helium next flows through a 3 µm silver filter and into a capillary system embedded in a 3.2 mm (1/8 inch) diameter titanium tube with a 0.4 mm (0.016 inch) wall thickness that takes the helium to a small reservoir, called the 1 K pot or simply the pot (Fig. 2). The helium passes through the impedance of the capillary system at 4.2 K and cools to 1.1 K by the time it reaches the 1 K pot. The thermal conductance of the impedance is small to minimize the heat flow from the 4.2 K reservoir to the pot. To minimize the chance of a complete blockage, four parallel polycarbonate capillaries (Paradigm Optics) are epoxied (with Stycast 2850 FT epoxy) within the titanium tube. Each has a 60 µm inner diameter and has 10 of its 20 cm length epoxied inside the tube.
Continuous-wave spontaneous lasing in mercury pumped by resonant two-photon absorption

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We demonstrate the first cw two-photon absorption laser-induced stimulated emission. The 7^1S_0 \rightarrow 6^3P_1 transition in mercury at a 1014 nm wavelength is used, and selective lasing of different isotopes is observed. © 2010 Optical Society of America
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Multiphoton processes are at the heart of many applications of photonics and quantum optics. Fascinating examples include upconversion lasers [1], multiphoton microscopy [2], and data storage in polymers [3]. Two-photon absorption can even drive spontaneous lasing, a process called two-photon absorption laser-induced stimulated emission [4], which can be used for plasma diagnostics [5]. Such two-photon pumped amplified spontaneous emission (ASE) was observed in mercury on the 7^3S_0 \rightarrow 6^3P_1 transition at 546 nm [6]. The cross section of multiphoton processes is often small compared to one-photon processes. High intensities are therefore necessary to reach enough gain for lasing, which could only be achieved with pulsed lasers, so far.

This Letter reports the first two-photon pumped cw laser. The two-photon excitation is enhanced by a near one-photon resonance. Continuous-wave laser powers of about 10–100 mW are therefore sufficient to induce ASE. We investigate threshold conditions for different mercury isotopes and compare two different pumping schemes as a function of buffer gas pressure in the mercury cell.

Figure 1 shows a simplified level scheme of mercury and the pumping transitions at the 254 nm and 408 nm wavelengths. Lasing occurs on the 7^1S_0 \rightarrow 6^3P_1 transition at the 1014 nm wavelength. In this scheme an additional green laser at 545 nm can be used to produce Lyman-α radiation (121.56 nm) by four-wave mixing [7]. Radiation at 254 nm comes from a frequency-quadrupled Yb:YAG disk laser, which generates up to 750 mW in the UV [8]. Radiation at 408 nm comes from a frequency-doubled titanium:sapphire laser with an output power of up to 450 mW in the blue. The pumping beams are focused by a lens of 15 cm focal length into a mercury cell with a vapor region of about 1.5 cm length. The IR light is separated from the pumping beams by an interference filter at 1014 nm and detected with a photodiode. Details of the mercury cell and the detection method are given elsewhere [9]. The beam waists in the focus are 8 μm (UV) and 10 μm (blue).

The detuning of the two lasers and the intensities of the laser fields can be used to control the population in the upper 7^1S_0 level. Its lifetime of 32 ns is long compared to the vacuum lifetime of the lower 6^3P_1 level (1.5 ns) [10], although the latter may be significantly increased by radiation trapping in dense mercury vapor [11]. Pumping into the upper level thus produces a population inversion on the 7^1S_0 \rightarrow 6^3P_1 transition, which yields ASE. To enhance the two-photon excitation, we choose a detuning in the UV of \(-25 \text{ GHz}\) relative to the 6^1S_0 \rightarrow 6^3P_1 one-photon resonance of the 202Hg isotope. At smaller detunings, resonant absorption of the UV beam is too large to efficiently pump the mercury vapor along the entire length of the cell.

Figure 2 shows the power of the IR light as a function of the UV power at the two-photon resonance of the 202Hg and 203Hg. The temperature of the mercury cell is 120 °C (mercury density \(N_{\text{Hg}} = 1.8 \times 10^{22} \text{ cm}^{-3}\)), the power of the blue beam is 45 mW, and no buffer gas is used. The insets show scans of the blue frequency across this resonance at different UV powers. Three different regimes can be distinguished and will be discussed in more detail in the next section: the first at low UV powers up to 4 mW (fluorescence), the second between 4 mW and 20 mW (threshold), and the third above 20 mW (lasing).

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In the fluorescence regime at low UV powers, the IR signal is proportional to the UV power. The scan across the two-photon resonance [see inset (a) of Fig. 2] shows several Voigt profiles resulting from isotope splitting of the $6^1S_0 - 7^1S_0$ resonance. The height of the peaks is related to the natural abundance of the isotopes $^{202}$Hg, 6.9%; $^{204}$Hg, 29.9%; $^{206}$Hg, 13.2%; $^{208}$Hg, 23.1%; $^{206}$Hg, 16.9%; and $^{158}$Hg, 9.97% [12], and the linewidth of 1.5 GHz is due to thermal Doppler broadening. The shape of the spectrum can be calculated using the optical Bloch equations of a three-level system [13].

In the threshold regime at intermediate UV powers, the gain of the pumped vapor region is large enough so that a lasing condition due to ASE occurs. The $^{202}$Hg isotope has the highest abundance and thus the lowest threshold condition. At the threshold regime, a steep increase in the IR power can be seen. Above the threshold of the $^{202}$Hg isotope but below the threshold of every other isotope, the IR light is dominated by the contribution of the $^{202}$Hg isotope. The spontaneous fluorescence of the other isotopes is many orders of magnitude smaller. The scan shows a single narrow peak at the two-photon resonance of the $^{202}$Hg [Fig. 2(b)].

In the lasing regime at high UV powers, all isotopes are above threshold and every isotope performs cw two-photon absorption laser-induced stimulated emission (CTALISE), as can be seen in inset (c) of Fig. 2. Comparing insets (a) and (b) of Fig. 2, one clearly sees that the linewidth of the IR signal is reduced in the regime of threshold. The broad excitation spectrum has to be multiplied with the nonlinear gain and is thereby narrowed.

There are two different excitation schemes to the $7^1S_0$ level. The first is a two-photon excitation. This means the sum of both laser frequencies is equal to the transition frequency of the $7^1S_0 - 6^1S_0$ transition. The second excitation scheme is a double one-photon excitation. In this case, an off-resonant excitation to the $6^3P_1$ level is followed by a resonant excitation into the upper $7^1S_0$ level. Therefore, the blue laser frequency is at the frequency of the $6^3P_1 - 7^1S_0$ transition. In Fig. 2, we use two different pumping schemes at different buffer gas pressures in the mercury cell. The detuning of the UV laser is $-25$ GHz. The pumping powers are about 200 mW UV and 245 mW blue, and the cell temperature is 120 °C. Helium is used as a buffer gas in a pressure range from 0 to 700 mbar. The maximum laser power at 1014 nm was 115 μW at a buffer gas pressure of 100 to 250 mbar and pumping with double one-photon excitation. Increasing buffer gas pressure causes more pressure broadening and thus to enhanced one-photon absorption at the UV wavelength. This effect has a different influence on both excitation schemes: for the double one-photon excitation, an enhanced UV absorption results in an enhanced excitation efficiency into the upper laser level. At buffer gas pressures above 300 mbar, the absorption at the UV wavelength is too high to efficiently pump the mercury along the entire cell and the IR power decreases. For the two-photon resonant excitation, in contrast, there is no pressure-related enhancement effect. UV absorption is a competing process instead. Increasing the buffer gas pressure decreases the UV power due to absorption. In addition, the density of Hg atoms in the ground state decreases due to excitation to the intermediate $6^3P_1$ level. The excitation probability by the competing two-photon process to the upper laser level decreases. Thus, the IR power produced by the two-photon resonant excitation decreases as the helium pressures increases.

Figure 4(a) shows a measured beam profile of the collimated IR beam at the exit window of the mercury cell. It
should be noted that a second beam propagates in the opposite direction and leaves the cell at the entry window. The input beam parameter products of the fundamental beams are $M_{uv}^2 = 1.7$ and $M_{blau}^2 = 1.6$. The resulting dark ring with about $1.4\, \text{mm}$ diameter originates from diffraction at apertures within the vacuum apparatus. To demonstrate the coherence properties of the IR light, a Michelson interferometer is set up. The beam is divided by a beam splitter and overlapped at the same beam splitter after passing the interferometer arms with arm lengths of about $20\, \text{cm}$. Figure 4(b) shows the beam profile after the interferometer with a clearly visible interference pattern. The coherence length estimated from the natural transition linewidth should be about $43\, \text{cm}$.

Our interest in nonlinear optics in mercury is driven by the need to generate radiation at Lyman-$\alpha$ ($121.56\, \text{nm}$) for future laser cooling of antihydrogen in a magnetic trap. Mercury vapor is a good candidate for an efficient cw Lyman-$\alpha$ source by four-wave mixing [7]. Amplified spontaneous emission is a possible competing process to Lyman-$\alpha$ generation [14]. To investigate if the four-wave mixing efficiency is reduced by the ASE at higher powers, we measure the vacuum UV (VUV) power generated by adding a third laser at the $545\, \text{nm}$ wavelength (see Fig. 1) in the presence of CTALISE. For details of VUV generation see [7]. Figure 5 shows a linear dependence of the Lyman-$\alpha$ power on the UV power. In a four-wave mixing process, the power generated is proportional to the power in each of the fundamental beams [14]. The submicrowatt of IR lasing does not significantly affect the power in the fundamental beams, and thus the four-wave mixing is unaffected by the weak IR lasing. The measurement was done at a UV detuning of $-150\, \text{GHz}$, a mercury cell temperature of $153\, \text{°C} (N_{\text{Hg}} = 7.1 \times 10^{22} \, \text{m}^{-3})$, a buffer gas pressure of $0\, \text{mbar}$, and using the two-photon resonant scheme. The laser powers are $98\, \text{mW}$ in the blue and $189\, \text{mW}$ in the green.

In conclusion, CTALISE is realized for the first time (to our knowledge). The threshold condition of different isotopes is investigated. Efficient pumping to the upper laser level was performed with a double one-photon pumping scheme.

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