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Summary of ATRAP[+] Progress in 2002 for the SPSC

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Wonderful Progress During 2002

Last year we reported the first demonstration of positron cooling of antiprotons in a nested Penning trap [Phys. Lett. B **507**, 1 (2001)]. We expressed excitement about this demonstration because it was a very promising way to produce cold antihydrogen – owing to the way it made it possible to make a prolonged interaction of cold antiprotons and positrons at a very low relative velocity.

The year 2002 showed that this optimism was well founded. Antihydrogen atoms were observed for the first time – all realized during the positron cooling of antiprotons in a nested Penning trap. We had long ago invented the nested Penning trap just for this purpose, and used electrons and protons to first demonstrate its usefulness.

The “stacking” or accumulation of cold antiprotons in a trap from successive pulses of antiprotons from the AD is another important technique, being used in all of the observations of cold antihydrogen. Although we first demonstrated this technique many years ago at LEAR, we presented a much more detailed study of stacking in 2002 owing to the central importance of this technique at the AD.

> "Stacking of Cold Antiprotons",
> G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch, E.A. Hessels
> Phys. Lett. B **548**, 140 (2002).

ATRAP’s two reports on the observation of cold antihydrogen both used electric field ionization to provide a unique and robust way to identify the production of cold antihydrogen. The first of these reports is

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

Antihydrogen was produced at an extremely high rate, as we had anticipated for a process that started with the three body recombination of involving one antiproton and two positrons. An important feature of these observations is that they are completely free of any background, requiring no subtraction of a substantial background of false events.

The second ATRAP report is

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

The antihydrogen production rate was greatly increased by repeatedly heating antiprotons from one side to the other of a nested Penning trap. During each cycle positrons cooled the antiprotons, and antihydrogen was formed.

The production rate was high enough that we were able to separate the antihydrogen production and detection regions by about 4 cm, and to apply an electric field between these two regions to analyze for the first time the antihydrogen states that were produced. By changing the distance between the antihydrogen production regions, we were also able to show that the production rate decreased with increasing separation distance, consistent with a $1/r^2$ dependence.

Long ago, ATRAP members laid out the goal to produce antihydrogen cold enough for trapping and spectroscopy. For more than 15 years we have been developing crucial techniques that have now made cold antihydrogen possible. The wonderful observations of cold antihydrogen in 2002 demonstrate substantial progress toward the still distant and difficult goal of antihydrogen trapping and accurate spectroscopic comparisons of antihydrogen and hydrogen.

ATRAP Observations Were Widely Reported

Tremendous publicity was generated by the two ATRAP Phys. Rev. Lett. reports announcing the observation and state-analysis of cold antihydrogen. While such publicity is never the motivation or justification for scientific research, it is also good for science if press accounts allow the public that funds the science to also appreciate and enjoy it. As examples, articles from Physics Today, Science and Nature are appended to this report.

2003

In preparation for the 2003 antiproton run we are improving both of two apparatuses that we used to observe cold antihydrogen in 2002. There is little new to say about our objectives since these remain much as they have been laid out in the initial ATRAP proposal and subsequent progress reports. Objectives include:

1. Increasing the number of positrons by increasing the diameter of the rotating electrode.
2. Increasing the number of positrons by improving our positron recycling techniques.
3. Studying the collisional deexcitation of excited states of cold antihydrogen.
4. Completing our experiments to make state-selected antihydrogen. We use lasers to produce Rydberg Cs. With a resonant charge exchange collision we transfer this excitation to positronium made by collisions between the Cs and trapped positrons. With a second charge exchange collision, between the positronium and trapped antiprotons, we transfer this excitation to antihydrogen. We almost made this work last fall.
5. Begin experiments to use lasers to deexcite antihydrogen to the lowest possible states.
6. Begin laser stimulated recombination experiments.

Last year it became clear that some of the medium and high energy experimenters in the committee were less comfortable with the field ionization techniques that we were pursuing, than with a more traditional particle detection of antihydrogen, by detecting a simultaneous annihilation of a positron and an antiproton when an antihydrogen atom hits a solid surface. Hopefully the two ATRAP reports illustrate important advantages of the ATRAP field ionization method:

1. Absences of background and background subtraction.
2. First way to analyze the states of the antihydrogen that were produced.

We of course intend to continue with this robust detection method.

Concerns and Opportunity

We wish that the number of weeks that antiprotons are available during 2003 was being increased rather than decreased, since one frustration is that the data rate is very slow at the AD. We can only make an attempt or two per hour to make cold antihydrogen, and we typically have only an eight hour shift each week day. Despite the challenge, we are confident that progress will continue during 2003.

The plan to shut down CERN antiprotons production for a year to conserve funds for LHC construction and commissioning is not optimal for ATRAP. Progress toward the precise spectroscopic comparison of antihydrogen and hydrogen will stop, or at least slow dramatically, during this shut down.

One possible way to turn the shut down to some advantage would be to use this time to install an RFQ that can be used by ATRAP and ATHENA to increase the antiproton accumulation efficiency. Although ASACUSA still has a long way to go to demonstrate the low energies and cryogenic vacuums that ATRAP requires, a very substantial potential increase in efficiency seems possible. We are beginning to investigate this possibility and to explore funding possibilities.

Summary

The exciting progress brings ATRAP closer to the difficult goal of using extremely accurate laser spectroscopy to probe for any tiny differences between the structure of antihydrogen and hydrogen, thereby providing the most precise test of CPT invariance with leptons and baryons.

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Stacking of cold antiprotons

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Abstract

The stacking of cold antiprotons is currently the only way to accumulate the large numbers of the cold antiprotons that are needed for low energy experiments. Both the largest possible number and the lowest possible temperature are desired, especially for the production and study of cold antihydrogen. The antiprotons accumulated in our particle trap have an energy 10^{10} times lower than the energy of those delivered by CERN's Antiprotons Decelerator (AD). The number accumulated (more than 0.4 million in this demonstration) is linear in the number of accepted high energy antiproton pulses (32 in this demonstration). Accumulation efficiencies and losses are measured and discussed.

1. Introduction

The existence of antihydrogen atoms was confirmed by the observation of high speed atoms formed in a storage ring, first at CERN [1] and then at Fermilab [2]. Cold antiprotons and positrons enabled us to observe positron-cooling of antiprotons [3], an important step towards the long term goal to produce antihydrogen that is cold enough to confine in a neutral particle trap for precise spectroscopic comparisons with hydrogen [4]. Such a comparison has the potential to substantially improve the accuracy of CPT tests with baryons and leptons [5] and to test for possible extensions to the standard model [6], owing to the high precision attainable with laser spectroscopy [7].

Only if substantial numbers of cold antiprotons are available does it become possible to produce cold antihydrogen that can be trapped for spectroscopy. Collisions with cold matter walls, of course, will cause annihilation before cooling, so the technique used to cool hydrogen for trapping and spectroscopy [8] is not

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an option. "Cold" here refers to cryogenic temperatures, near 4 K or below, since antihydrogen hotter than this is not so useful for particle trapping. Only approximately a percent of antihydrogen atoms from a 4 K thermal distribution can be held in a state-of-the-art superconducting neutral particle trap, about 0.5 K deep for the magnetic moment of ground state antihydrogen atoms. This percentage drops very rapidly with increasing temperature, so hotter antihydrogen atoms will be difficult to capture.

This Letter reports the substantial accumulation of cold antiprotons in an ion trap—up to 0.4 million antiprotons from a sequence of 32 pulses of high energy antiprotons sent to our apparatus. The stacking of cold antiprotons is linear in the number of injection pulses, suggesting that as many antiprotons can be accumulated as time permits. Although some of us demonstrated the basic principles more than a decade ago [5, 9], there was little need for more cold antiprotons at the time. The observed stacking was thus only described briefly, but never investigated extensively nor discussed in the detail that its current importance warrants. All of the current experiments with low energy antiprotons have adopted this technique, to accumulate antiprotons from the CERN Antiproton Decelerator, the only source of antiprotons that can be so cooled and stored. In the future, a radiofrequency quadrupole (RFQ) decelerator together with stacking may allow the accumulation of larger numbers of cold antiprotons [10].

2. Capture of keV antiprotons

Low energy antiproton studies are currently done only at the Antiproton Decelerator (AD), a storage ring built at CERN primarily to make antiprotons available for antihydrogen studies. It delivers 5.3 MeV antiprotons—an energy that is more than 10^{10} times higher than $kT = 0.3$ meV for our 4 K trap. Every 108 seconds a pulse of up to 3×10^7 antiprotons is sent from the AD to an attached experiment. By slowing these in matter [11], trapping them [12], and electron-cooling them in the trap [9], of order 20 000 cold antiprotons are stored from one injection. More cold antiprotons are currently available only if antiprotons are stacked from successive pulses of AD antiprotons, using the technique demonstrated and discussed here.

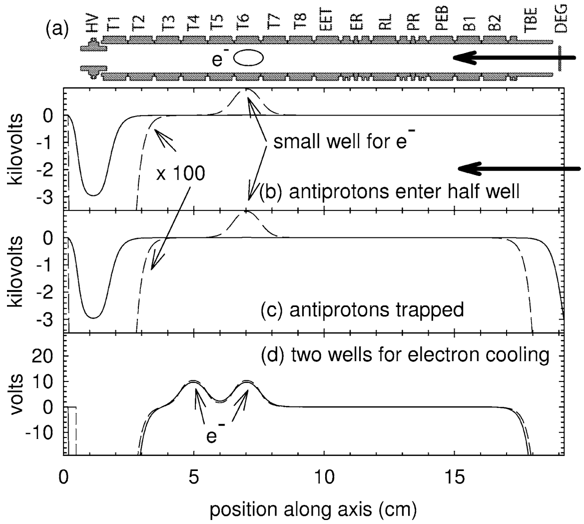

Fig. 1. (a) Cross section of the electrodes used to accumulate cold antiprotons. Voltage applied to the electrodes form different potential well on axis when we await antiprotons (b) and capture and electron-cool antiprotons in one (c) or two (d) electron wells.

Antiprotons are captured and cooled within a Penning trap. A 5.4 Tesla magnetic field from a superconducting solenoid is directed along the vertical axis of a stack of copper ring electrodes (Fig. 1(a)) with a 1.2 cm inner diameter. The electrodes and surrounding vacuum enclosure are cooled to 4.2 K via a thermal contact to liquid helium. Cryopumping reduces the pressure within the trap to less than 5×10^{-17} Torr (7×10^{-15} Pa and 7×10^{-17} mbar), as measured in a similar apparatus [9] using the lifetime of trapped antiprotons as the vacuum gauge.

With the trap biased to form half a potential well (Fig. 1(b)), a pulse of antiprotons from the AD enters from the bottom (arrow from right in the figure), some of them slowing below 3 keV as they pass through the thin beryllium window (labelled as degrader DEG). These slower antiprotons, guided by the 5.4 Tesla magnetic field directed along the axis of the trap, reflect from the potential barrier at the top of the trap. Before they can return to the entrance of the trap and escape, the potential on the thin window degrader is made suddenly negative (Fig. 1(c)) to capture the antiprotons. We refer to this potential well that extends the whole length of the trap as the "long well". We do so to distinguish it from the "short well" just visible in the expanded view of the potentials (electrode T6

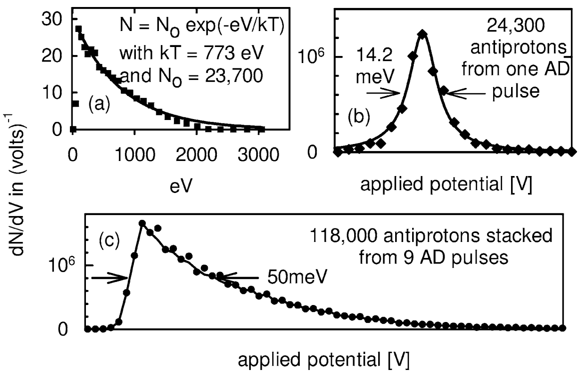

Fig. 2. Energy spectra for antiprotons trapped from a single pulse from the AD without (a) and with (b) electron cooling. Stacking (c) yields a much larger number of cold antiprotons. The insets to (b) and (c) indicate the linear voltage scale; no absolute voltages are given since tiny offset voltages are not calibrated.

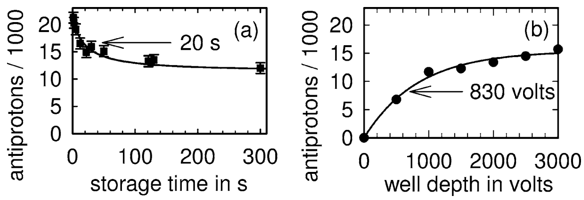

Fig. 3. Number of antiprotons captured from an AD pulse has approximately an exponential dependence upon storage time (a) and well depth (b) with the $1/e$ values indicated.

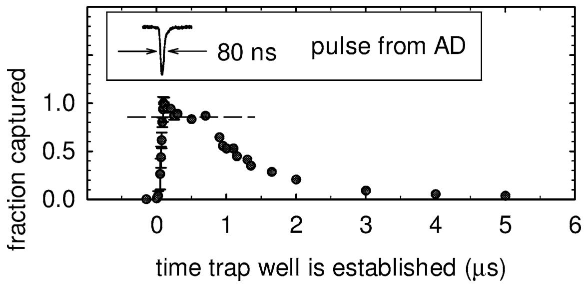

Fig. 4. Number of trapped antiprotons depends upon when the trapping potential is applied.

in Fig. 1(b) and (c)) that will be central in the coming discussion of electron-cooling and stacking.

The number and energy distributions of the hot antiprotons captured is measured by slowly ramping the potential of the degrader window back through zero. The highest energy antiprotons escape first and the charged pions from their annihilation are detected with essentially unit efficiency in scintillators that surround the trap apparatus [3]. Antiprotons held for tens of seconds or more show a characteristic energy spectrum that is nearly exponential (Fig. 2(a)). Almost 25 000 antiprotons have been captured in the long well from the most intense AD pulses, but 13 000–16 000 is more typical. Typically 7×10^{-4} of the antiprotons ejected from the AD are in our long well after 30 seconds, slightly higher than reported for a similar trap at LEAR [5].

These numbers refer to antiprotons remaining after losses we observed during the first seconds of antiproton capture (Fig. 3(a)) as captured antiprotons collide and some leave the trap. The number of captured antiprotons increases as the depth of the long potential well is increased (Fig. 3(b)). One might expect this increase to be linear insofar as the energy distribution of antiprotons slowed in the degrader window is expected to be hundreds of keV—much wider than the energy of antiprotons we can capture. However, we observe that the number captured saturates, presumably because particles with more energy along the trap axis also typically have more radial energy and this can cause them to hit the trap electrodes. It may be that a trap with a larger radius may restore a linear increase in trapped particles with well depth.

The 80 ns duration of the entering pulse of antiprotons (inset to Fig. 4) is narrow compared to the typical round trip time for captured antiprotons. Antiprotons with the average energy of 773 eV in Fig. 2(a), for example, have a round trip time of 900 ns. Fig. 4 shows how the maximum number of antiprotons are captured in the long well by making the sudden potential change just after the pulse of antiprotons enters the trap. Delaying this potential change decreases the number of captured antiprotons since the faster ones return to hit the degrader window before capture. The number of captured antiprotons stays rather flat (dashed line segment in the figure) during the round trip time it takes for the faster antiprotons to return to the trap entrance.

3. Electron cooling and stacking

Electrons for electron cooling are loaded for these studies using a positron beam sent through the trap. It creates secondary electrons when it strikes the degrader (DEG). We capture these electrons and transfer them to electrode T6 before accepting antiprotons into the trap. The details of the electron loading are not so important for our purposes here since we often instead load electrons using a field emission point as has been described before [9]. For these studies, about 4 million electrons are used. Their cyclotron motion cools via the spontaneous emission of synchrotron radiation with a 0.1 second time constant, and their oscillatory axial motion along the magnetic field direction cools via collisional coupling to the cyclotron motion. Magnetron motion is not cooled for these studies.

With cold electrons ready for electron cooling, antiprotons are captured into the long well as described above. Fig. 5 shows the shifting energy spectrum of antiprotons remaining in the long well for increasing electron cooling times. Cooled antiprotons join the electrons in the small well and hence do not show up in these spectra. Antiprotons away from the center of the trap, outside the 4 mm radius of the electron cloud, are not electron-cooled even after a long time in the trap. Fig. 6 shows how many antiprotons are captured in the long well, not cooled by the electrons, cooled into the small well, and spilled from the long well from a single pulse of antiprotons from the AD. The number of annihilations of antiprotons that spill from the trap is plotted as a function of time in Fig. 7(a). Presumably these antiprotons are barely bound in the trap and are nudged out by collisions with other antiprotons. Two AD injection cycles are shown in this figure. The narrow peaks occur when antiprotons are released from the long well to analyze their energies, and to prepare for the next AD pulse.

We eject the electrons in the small well with the cooled antiprotons by repeatedly opening the small potential well for 100 ns. The less massive electrons escape leaving the heavier antiprotons behind to be recaptured when the well is restored. Fig. 2(b) and (c) shows spectra of antiprotons released as the depth of the small well is slowly reduced and the number of antiproton annihilations is measured as a function of the well depth. The widths of the observed low energy distributions (Fig. 2(b) and (c)) are difficult to interpret. The electrons are in thermal equilibrium with their 4 K environment, and the antiprotons in turn come to thermal equilibrium with the electrons. A 4 K energy width is only 0.3 meV. This is much smaller than the observed widths, which depend upon space charge [9] (about 10 mV is estimated for

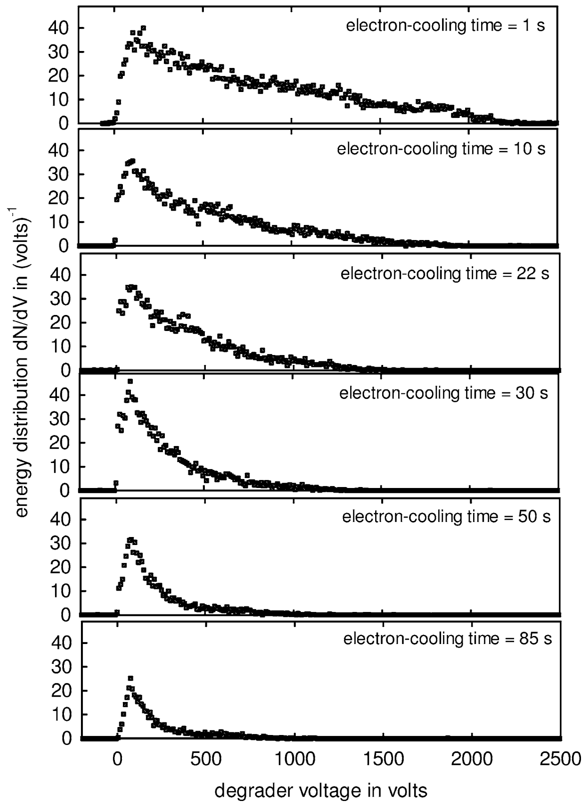

Fig. 5. The energy of the antiprotons in the long well decreases as a function of electron cooling time. The number also decreases insofar as some antiprotons are cooled into the small well and others are lost from the trap.

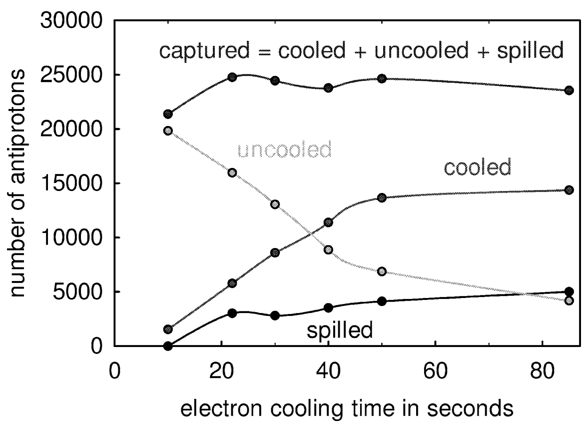

Fig. 6. Number of antiprotons captured, uncooled, spilled and cooled from a single pulse of AD antiprotons.

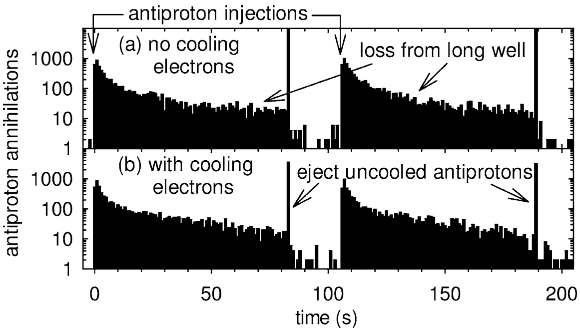

Fig. 7. AD antiprotons are injected into the long trap every 108 s. For the subsequent 85 s, with or without cooling electrons, the number lost is approximately the same, but electrons cool some into the small well (or wells). Uncooled antiprotons remaining in the long well are then ejected.

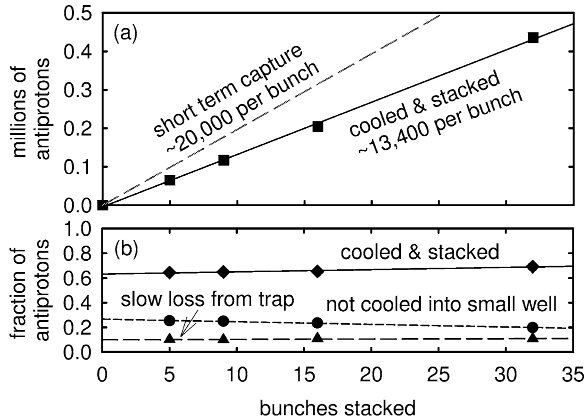

Fig. 8. Stacking successive pulses of antiprotons.

25 000 antiprotons) and upon radial dependences of the trapping field (typically 20% variations for a 6 mm radius, or about 10 mV). There is also adiabatic cooling as the well depth is reduced.

If more than 20 000 cold antiprotons are desired then it is necessary to accumulate antiprotons from more than one pulse of antiprotons from the AD. After cooling antiprotons from one AD pulse for 85 seconds, as described above, the cooled antiprotons reside with the electrons in the small well. We then remove the high voltage potential on the degrader window, and count the uncooled antiprotons thereby released from the long well. The long trap is now ready to capture and cool a second pulse of antiprotons from the AD. Fig. 7 shows a time record of antiproton annihilations detected as antiprotons are injected into the trap, held with and without electron-cooling, and then released.

The basic idea of antiproton stacking in a trap is to accumulate cold antiprotons from as many pulses from the AD as we like. Some of us demonstrated such stacking long ago, but only for a few pulses of antiprotons [9]. The applications at the time did not require many antiprotons, and LEAR pulses delivered about 100 times more antiprotons than the AD delivers. The crucial demonstration in this report is the linear accumulation of cold antiprotons as a function of the number of AD antiproton pulses injected into the trap in Fig. 8(a). We have accumulated up 18 000 antiprotons per AD pulse when the AD was operating at its best (16 000 is more typical) but for these systematic studies the accumulation rate was lower. The dashed line above in this figure includes antiprotons that are initially captured in the trap, but then spilled quickly as discussed. We continuously monitor all antiproton annihilations during the whole process, except for 2 to 10 seconds following an AD pulse during which our detectors are turned off to protect them from the large injection signal.

The near unit detection efficiency allows us to identify antiproton losses at nearly any time during the cycle. Fig. 8(b) gives more details. About 20% of the initially captured antiprotons are not cooled by the electrons and are lost when the long well is opened to prepare for accepting the next pulse. About 10% of the initially captured antiprotons are lost from the traps during the electron cooling process. A little more than 60% of the initially captured antiprotons are cooled into the small well and are available for as long as desired for experiments.

Since the antiprotons that spill from the trap during the cooling time, whether or not cooling takes place, are not really trapped for any significant time, a convenient way to normalize is to compare the number of antiprotons accumulated in the small well per antiproton pulse to the number of antiprotons captured in the long well when no cooling electrons are in the small well [9]. This ratio is typically 1.0 for the 85 second electron cooling time we generally use. This efficiency depends upon the details of the number and spatial distribution of the cooling electrons, the number of wells these are contained in, etc.

The antiproton stacking study in Fig. 8 was carried out with electrons in only the T6 potential well

(Fig. 1(a)). We have observed that if we stack more than the 30 bunches shown, the “slow” loss from the long well between injections (Fig. 7) increases sharply, keeping us from accumulating more cold antiprotons. We then must use multiple wells for electron-cooling to accumulate more antiprotons. Fig. 1(d) shows a two well structure we have used, and we have used more wells.

We have loaded more cooling electrons using a field emission point near the center axis of the trap. This is much faster with the result that we typically loaded 8 million electrons for electron cooling. This larger number of electrons occupied a volume that extended to larger radii (about 5 mm), away from the trap axis. As might be expected, fewer antiprotons were left uncooled by the cooling electrons in this case, about 5%. However, the “slow” loss increases to 35% to just compensate.

4. Conclusions

In conclusion, cold antiprotons with temperatures near to 4 K can be accumulated from a sequence of pulses of high energy antiprotons. The crucial result is that cold antiprotons accumulate in proportion to the number of high energy antiproton pulses sent to the trap. Electron-cooling is key to this stacking technique. A careful measurement of antiproton losses during the accumulation process indicates where further optimization can be sought. Meanwhile, antiprotons can be accumulated linearly in time for low energy experiments where larger numbers of cold antiprotons are needed than can be obtained from single pulses of high energy antiprotons. Experiments to produce cold antihydrogen, for example, will rely on this antiproton stacking techniques.

Acknowledgements

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Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

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A background-free observation of cold antihydrogen atoms is made using field ionization followed by antiproton storage, a detection method that provides the first experimental information about antihydrogen atomic states. More antihydrogen atoms can be field ionized in an hour than all the antimatter atoms that have been previously reported, and the production rate per incident high energy antiproton is higher than ever observed. The high rate and the high Rydberg states suggest that the antihydrogen is formed via three-body recombination.

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Antihydrogen ($\overline{\mathrm{H}}$) atoms that are cold enough to be trapped for laser spectroscopy [1] promise to provide the most stringent *CPT* tests with baryons and leptons [2], along with more sensitive tests for possible extensions to the standard model [3], building on the high accuracy of hydrogen spectroscopy [4]. It may even be possible to directly observe the gravitational force on antimatter atoms [5]. $\overline{\mathrm{H}}$ atoms with a temperature near to the 0.5 K depth of a realistic magnetic trap are greatly preferred since trapping atoms from a thermal distribution is much less likely with increasing temperature.

The ATRAP Collaboration demonstrated the first positron cooling of antiprotons [6,7] in a nested Penning trap [8] more than a year ago. Detailed studies of this cooling (to 4 K) have since been carried out [9] to ensure that the antiproton ($\overline{p}$) loss we observed during positron (e^+) cooling corresponds to $\overline{\mathrm{H}}$ formation. This Letter reports an observation of cold $\overline{\mathrm{H}}$ produced during such cooling that is insensitive to other $\overline{p}$ loss mechanisms. Field ionization of $\overline{\mathrm{H}}$ followed by $\overline{p}$ storage provides the first experimental information about $\overline{\mathrm{H}}$ excited states. Every recorded event comes from $\overline{\mathrm{H}}$ production, with no background. Another very recent report of cold $\overline{\mathrm{H}}$ formation [10], also during positron cooling in a nested Penning trap, instead identifies $\overline{p}$ and e^+ annihilations within ± 8 mm and 5 μs as $\overline{\mathrm{H}}$, subtracting a background larger than the signal. Observations of high velocity $\overline{\mathrm{H}}$ also used simultaneous annihilation detection [11,12].

More antiprotons from ionized $\overline{\mathrm{H}}$ atoms can now be captured in an hour than the sum of all antimatter atoms reported so far. If the $\overline{\mathrm{H}}$ leave the production region isotropically, then 11% of the $\overline{p}$ in the nested Penning trap form $\overline{\mathrm{H}}$. The 657 $\overline{p}$ we capture from $\overline{\mathrm{H}}$ ionization in the sample used here would then correspond to nearly 170 000 cold $\overline{\mathrm{H}}$ atoms. Even if the distribution is not isotropic, the high rate supports the feasibility of spectroscopic investigations to follow. Rydberg states formed at a high rate likely start with a three-body recombination collision [8] between a $\overline{p}$ and two e^+, with deexcitation continuing via other processes [13,14].

The apparatus (Fig. 1) alternates between the one used to demonstrate positron cooling of antiprotons [6] and a close copy. A 5.4 T magnetic field from a superconducting solenoid is directed along the vertical symmetry axis of a stack of gold-plated copper rings. Applied voltages form Penning traps that confine the $\overline{p}$, e^-, and e^+ and control their interactions. Captured $\overline{p}$ accumulate in the volume below the rotatable electrode. Above, injected e^+ accumulate simultaneously. The electrodes and surrounding vacuum enclosure are cooled to 4.2 K via a thermal contact to liquid helium. Cryopumping reduces the pressure within the trap to less than 5×10^{-17} Torr, as measured in a similar apparatus [15] using the lifetime of trapped $\overline{p}$ as a gauge.

All experiments pursuing antihydrogen, and other experiments requiring the lowest energy antiprotons, make use of CERN's unique Antiproton Decelerator (AD). A standard set of techniques that some of us developed over the last 15 years [2] is also used to accumulate cold $\overline{p}$ in a trap, at an energy that can be more than a factor of 10^{10} times lower than that of $\overline{p}$ in the AD. Every 100 s, the AD ejects a short pulse of $\overline{p}$. The $\overline{p}$ slow in matter, are captured in a trap that is closed electronically while they are within, and electron cool in the trap to 4.2 K.

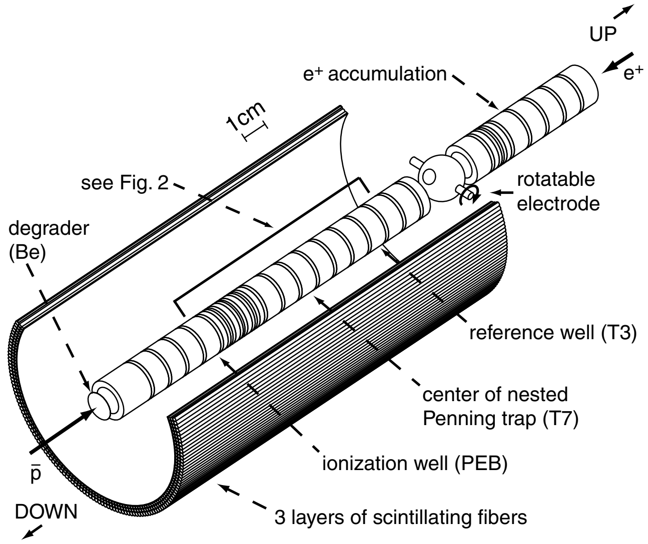

FIG. 1. Overview of the trap and detectors. Antiprotons are loaded from below (left), into the trap electrodes below the rotatable electrode. Positrons are simultaneously loaded from above (right) into the electrodes above the rotatable electrode. $\overline{\mathrm{H}}$ formation is observed within the lower region detailed in the next figure.

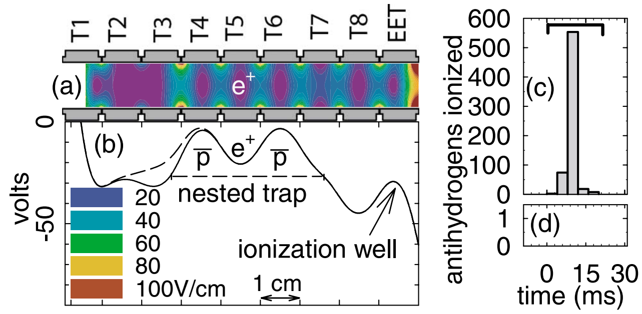

FIG. 2 (color). (a) Electrodes for the nested Penning trap. Inside is a representation of the magnitude of the electric field that strips $\overline{\mathrm{H}}$ atoms. (b) Potential on axis for positron cooling of antiprotons (solid line) during which $\overline{\mathrm{H}}$ formation takes place, with the (dashed line) modification used to launch $\overline{p}$ into the well. (c) Antiprotons from $\overline{\mathrm{H}}$ ionization are released from the ionization well during a 20 ms time window. (d) No $\overline{p}$ are counted when no e^+ are in the nested Penning trap.

A $\overline{p}$ stacking technique [16] allows the accumulation of as many $\overline{p}$ from successive AD pulses as time permits. Typically 150 000 antiprotons end up suspended within electrode T2 [Fig. 2(a)].

The accumulated e^+ [17] originate in a 69 mCi ^{22}Na source that is lowered through a He dewar to settle against the 4.2 K trap enclosure. Fast e^+ follow magnetic field lines and enter the trap vacuum through a thin Ti window. Some slow as they enter the trapping region through a thin single crystal of tungsten. Others slow while turning around within a thick tungsten crystal that rotates to the trap axis when the rotatable electrode goes to its closed position. Slow e^+ that pick up e^- while leaving the thin crystal form highly magnetized, Rydberg positronium atoms. These travel parallel to the trap axis until they are ionized by the electric field of a Penning trap well, whereupon the e^+ are captured. With the rotatable electrode in its closed position, neither crystal can be struck by $\overline{p}$, thus protecting an essential layer of adsorbed gas on the thin crystal, without which e^+ accumulation ceases [17,18]. With this electrode rotated open, e^+ can be pulsed through and caught in the lower trap region. Particle motions induce detectable currents in resonant *RLC* circuits attached to trap electrodes, making it possible to nondestructively detect the e^+ number before and after the transfer. Up to 1.7×10^6 cold e^+ are located in electrode T5 [Fig. 2(a)] for these studies.

The nested Penning trap [Figs. 2(a) and 2(b)] is central to the production of cold $\overline{\mathrm{H}}$. The e^+ and $\overline{p}$ have opposite charge signs, and thus cannot be confined or made to interact within the same Penning trap well. Some of us proposed the nested Penning trap [8], with e^+ within a small inverted well at the center of a larger well for $\overline{p}$, as the solution to this challenge. We investigated its properties with e^- and p [19], loaded cold $\overline{p}$ and e^+ together in a nested Penning trap [18], and then used it to observe the positron cooling of antiprotons [6].

To start positron cooling and $\overline{\mathrm{H}}$ formation, the $\overline{p}$ are launched into the nested Penning trap by pulsing from the solid to the dashed potential [Fig. 2(b)] for 1.5 μs. The $\overline{p}$ oscillate back and forth through the cold e^+ within a nearly symmetrical nested Penning trap, restored before the $\overline{p}$ return to their launch point. They lose energy via collisions with e^+, which cool via synchrotron radiation to the 4.2 K of their surroundings.

Antihydrogen should form most efficiently when e^+ cool $\overline{p}$ to the point where the two species have low relative velocities. Upon observing $\overline{p}$ losses during positron cooling, and intriguing indications of $\overline{\mathrm{H}}$ production, we undertook a more detailed study of positron cooling [9] to ensure that other mechanisms would not generate signals that could be confused with $\overline{\mathrm{H}}$ production. The ambipolar diffusion mechanism [20] is particularly troubling since unbound e^+ and $\overline{p}$ correlate enough to diffuse out of the trap, perhaps even generating simultaneous annihilations of $\overline{p}$ and e^+.

Detailed studies of the positron cooling of antiprotons in a nested Penning trap reveal some intricacy, as illustrated with small numbers of $\overline{p}$ and e^+ in Fig. 3. The average $\overline{p}$ energy decreases exponentially for short times [Fig. 3(a)], with a time constant that varies with the particle number and density. However, the $\overline{p}$ energy spectra taken at a sequence of cooling times [Figs. 3(b)–3(e)] reveals a great deal of structure, not yet completely understood. The $\overline{\mathrm{H}}$ atoms presumably form when the energies of the $\overline{p}$ (histograms) and e^+ (vertical dashed line) overlap, since their relative velocities are then lowest. On a 10 times longer time scale, the $\overline{p}$ cool into the side wells of the nested trap, out of contact with the e^+. The new cooling mechanism here seems to be a recycled evaporative cooling of the $\overline{p}$, whereby hot $\overline{p}$ that "evaporate" to higher energies in the nested well are cooled by the e^+ before they leave the well. With no e^+ in the nested well, evaporative cooling cools the $\overline{p}$ on the slower time scale. There is also radial loss of $\overline{p}$ near the potential maximum at the center of the nested Penning trap.

Any $\overline{\mathrm{H}}$ atom formed is free to move in the initial direction of its $\overline{p}$, unconfined by the nested Penning trap. $\overline{\mathrm{H}}$ atoms passing through the field-ionization well in a state that can be ionized by the electric field will leave their $\overline{p}$ trapped in this well. The ionization well [within electrode EET in Fig. 2(a)] is carefully constructed so that its electric field ensures that no $\overline{p}$ from the nested Penning trap can get into it (e.g., a $\overline{p}$ liberated from the nested well by ambipolar diffusion), except if it travels about 4 cm bound within an $\overline{\mathrm{H}}$ atom. Any $\overline{p}$ heated out of the nested Penning trap escapes over the lower potential barrier in the other direction. Even if a $\overline{p}$ did acquire enough energy to go over the ionization well in one pass it would not be trapped because there is no mechanism to lower its energy while over this well. In addition, positron cooling lowers the energy of the $\overline{p}$ in the nested well, taking them farther from the energy required to even pass over the ionization well.

Electric fields [Fig. 2(a)] ionize $\overline{\mathrm{H}}$ Rydberg states. Numerical modeling indicates the capture of $\overline{p}$ from $\overline{\mathrm{H}}$ atoms that ionize in electric fields between 35 and 95 V/cm. A rough estimate comes from the classical formula [21] for the electric field $F = 3.2 \times 10^8 n^{-4}$ V/cm that would strip a Rydberg atom entering this field. The binding energy, $E = 13.6 n^{-2}$ eV, defines n even though it is not a good quantum number in these fields. This suggests the field ionization and capture of $\overline{p}$ from $\overline{\mathrm{H}}$ atoms with binding energies corresponding to $n = 43$ to $n = 55$. Refined estimates are needed using methods suited to strong fields.

Only signals from $\overline{\mathrm{H}}$ are detected with this field-ionization method—there is no background at all. Figure 2(c) represents 657 ionized $\overline{\mathrm{H}}$ atoms captured in the ionization well during the course of this experiment—more than all of the $\overline{\mathrm{H}}$ atoms that have been reported so far. In many trials without e^+ we have never seen a single $\overline{p}$ in the ionization well [Fig. 2(d)]. Antiprotons from $\overline{\mathrm{H}}$ ionization are stored in the ionization well until after positron cooling is completed in the nested well, and all e^+ and $\overline{p}$ in the nested well are released in the direction away from the ionization well. We then eject the trapped $\overline{p}$ by ramping down the potential of the ionization well in 20 ms. The ejected $\overline{p}$ annihilate upon striking electrodes, generating pions and other charged particles that produce light pulses in the scintillators. The ramp is fast enough so that the 1.2 s^{-1} cosmic ray background contributes a count in our window only 1 time in 50 in Figs. 2(c) and 2(d). Our experimentally calibrated detection efficiency [22] corresponds to 1 in 2.7 of the stored $\overline{p}$ producing a coincidence signal in surrounding scintillators.

The number of ionized $\overline{\mathrm{H}}$ atoms increases with the number of e^+ in the nested well [Fig. 4(a)] as might be expected, though this curve is surprisingly insensitive to the total number of e^+ for larger e^+ number. We are exploring some indications that the shape of this measured curve is related to a quadratic dependence of the production rate upon e^+ density. The ionization well can be moved farther away from the center of the nested well, using identical electrodes to the right of EET in Fig. 2(a). The decrease in the number of ionized $\overline{\mathrm{H}}$ [Fig. 4(b)] seems consistent with a quadratic dependence on distance, showing that the $\overline{\mathrm{H}}$ angular distribution is broader than the small solid angle subtended by our ionization well. Isotropic $\overline{\mathrm{H}}$ production and a broad $\overline{\mathrm{H}}$ "beam" along the direction of the magnetic field are both consistent

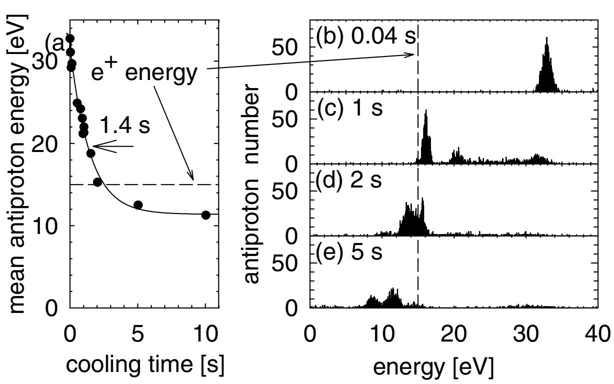

FIG. 3. (a) Antiproton average energy decreases exponentially in time until the antiprotons and positrons have the lowest relative velocity. Cooling then continues but at a 10 times slower rate. (b)–(e) Energy spectra of the $\overline{p}$ as a function of the positron cooling time. (For this example, 5000 $\overline{p}$ are used, along with 200 000 e^+ in a 15 V well.)

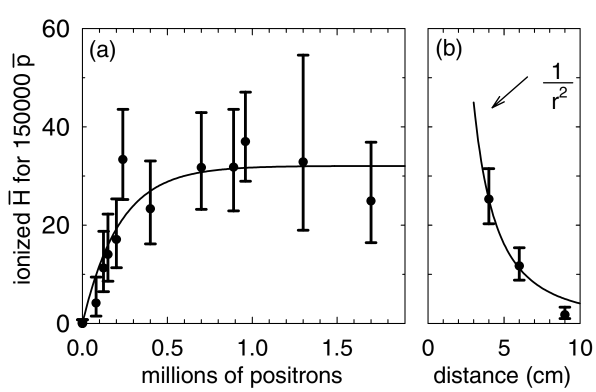

FIG. 4. (a) The number of field-ionized $\overline{\mathrm{H}}$ atoms increases with the number of e^+ in the nested Penning trap of Fig. 2, and then levels off. (b) This number decreases when the ionization well is moved away from the nested Penning trap.

with Fig. 4(b). More study is required to see if the trajectories of the highly polarizable Rydberg atoms could be significantly modified by the electric and magnetic fields.

To give some idea of how efficiently $\overline{\mathrm{H}}$ atoms are stripped and detected we use one trial in which eight AD injection pulses are used to accumulate 148 000 cold $\overline{p}$, with 430 000 cold e^+ accumulating simultaneously. After the positron cooling of the antiprotons we determine that 66 $\overline{\mathrm{H}}$ atoms have field ionized and left their $\overline{p}$ in the ionization well. This means that we observe about eight $\overline{\mathrm{H}}$ atoms per AD injection pulse, and about one $\overline{\mathrm{H}}$ atom per 2200 antiprotons in the nested well. (For comparison, smaller values of about $1/4$ and $1/12\,000$ pertain to the very recent implementation of positron cooling of $\overline{p}$ in a larger trap using more e^+ [10], perhaps because of a higher temperature and a higher background gas pressure.)

If the $\overline{\mathrm{H}}$ production at ATRAP is isotropic, then the 657 ionized $\overline{\mathrm{H}}$ would represent nearly 170 000 cold $\overline{\mathrm{H}}$. This would mean that a remarkable 11% of the $\overline{p}$ in the nested Penning trap are forming $\overline{\mathrm{H}}$ atoms — comprising a substantial portion of the large $\overline{p}$ losses we have been observing during positron cooling of antiprotons since this cooling was first observed. (The ionization well covers only about $1/260$ of the total solid angle.)

In conclusion, more $\overline{\mathrm{H}}$ atoms are observed than the sum of all previously reported, and many more are observed per high energy $\overline{p}$ sent to our apparatus, and per $\overline{p}$ cooled in our apparatus. $\overline{\mathrm{H}}$ atoms are produced during positron cooling of antiprotons in a nested Penning trap. Improved implementations of such cooling will certainly increase the $\overline{\mathrm{H}}$ production rate. Repeatedly driving $\overline{p}$ from one side of the nested well to the other with a resonant radio frequency drive, for example, yields 720 ionized $\overline{\mathrm{H}}$ atoms in 1 h [9]. The $\overline{\mathrm{H}}$ signals being observed should allow optimization of techniques and further rate increases.

The electric field ionization of $\overline{\mathrm{H}}$, followed by $\overline{p}$ storage until all $\overline{p}$ losses cease, allows the detection of $\overline{\mathrm{H}}$ atoms without any background at all; only $\overline{\mathrm{H}}$ atoms are observed. The field ionization also gives the first glimpse of $\overline{\mathrm{H}}$ atomic states, with n roughly between about 43 and 55 here. Changing the ionizing electric field should reveal a more detailed picture and indicate how difficult it may be to deexcite $\overline{\mathrm{H}}$ atoms to states that can be trapped and used for spectroscopic studies. It will be interesting to see if the highly polarizable Rydberg states could be trapped in an electric field minimum for some time, but trapping of $\overline{\mathrm{H}}$ in a magnetic trap superimposed on the Penning traps for charge particles [23] awaits deexcitation of the highly magnetized, highly excited states that have been observed.

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Driven Production of Cold Antihydrogen and the First Measured Distribution of Antihydrogen States

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Cold antihydrogen is produced when antiprotons are repeatedly driven into collisions with cold positrons within a nested Penning trap. Efficient antihydrogen production takes place during many cycles of positron cooling of antiprotons. A first measurement of a distribution of antihydrogen states is made using a preionizing electric field between separated production and detection regions. Surviving antihydrogen is stripped in an ionization well that captures and stores the freed antiproton for background-free detection.

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Observations of cold antihydrogen ($\overline{\rm H}$) were recently reported by the ATHENA [1] and ATRAP [2] collaborations. Both used nested Penning traps, proposed [3] and developed [4,5] to allow oppositely charged antiprotons ($\overline{p}$) and positrons (e^+) to interact while confined. Both observed $\overline{\rm H}$ production during the positron cooling of antiprotons in a nested Penning trap, following the earlier ATRAP demonstration [6]. The two experiments differed sharply in the way that cold $\overline{\rm H}$ was detected. ATHENA identified $\overline{p}$ and e^+ annihilations within ± 8 mm and 5 μs as $\overline{\rm H}$, subtracting a background (from $\overline{p}$ annihilations generating e^+e^-) that was larger than the signal. No information about the $\overline{\rm H}$ states was provided [1]. ATRAP used a background-free, field-ionization method to detect more $\overline{\rm H}$ in an hour than all other reported $\overline{\rm H}$ observations. The first glimpse of $\overline{\rm H}$ states was provided insofar as states ionized by electric fields between 35 and 95 V/cm were detected [2].

More knowledge of $\overline{\rm H}$ excited state distributions is required to prepare states that can be trapped and used for precision spectroscopy. This long term goal [7] remains attractive for greatly improved *CPT* tests with baryons and leptons [8] and sensitive tests of extensions to the standard model [9], building on accurate hydrogen spectroscopy [10]. It may even be possible to directly observe the gravitational force on cold antimatter atoms [11].

In this Letter, a measured distribution of $\overline{\rm H}$ states is reported for the first time, for $\overline{\rm H}$ produced at a high rate by driving $\overline{p}$ into collisions with cold e^+. The $\overline{\rm H}$ states are analyzed as they pass through an electric field that is varied without changing the separated $\overline{\rm H}$ production and detection. The $\overline{p}$ are resonantly driven through trapped e^+, back and forth from one side of a nested Penning trap to the other, in a new and efficient $\overline{\rm H}$ production method. $\overline{\rm H}$ forms during the positron cooling of antiprotons over many cycles, until most of the trapped $\overline{p}$ have formed $\overline{\rm H}$ or are otherwise lost from the trap. A higher $\overline{\rm H}$ production rate, per $\overline{p}$ coming to our apparatus, compensates for the reduced detection solid angle caused by the clean spatial separation of production and detection. The high rate and observed Rydberg states are what is expected for a three-body recombination mechanism [3,12,13].

The apparatus and many techniques are similar to those ATRAP used to first demonstrate positron cooling of antiprotons in a nested Penning trap [6], and to observe the cold $\overline{\rm H}$ produced during this cooling [2]. A $B = 5.4$ T magnetic field from a superconducting solenoid is directed along the symmetry axis of a stack of gold-plated copper rings (Fig. 1). Applied voltages form Penning traps [Figs. 2(a) and 2(b)] that confine the $\overline{p}$, e^-, and e^+, and control their interactions. The electrodes and surrounding vacuum enclosure are cooled to 4.2 K via thermal contact to liquid helium. Cryopumping reduces the pressure within the trap to less than 5×10^{-17} Torr, as measured in a similar apparatus using the lifetime of trapped $\overline{p}$ as a gauge [14].

Antiprotons from CERN's Antiproton Decelerator (AD) are slowed, trapped, electron cooled, and stacked [8,15] in the volume below the rotatable electrode. Above, positrons from a ^{22}Na source slow and form Rydberg

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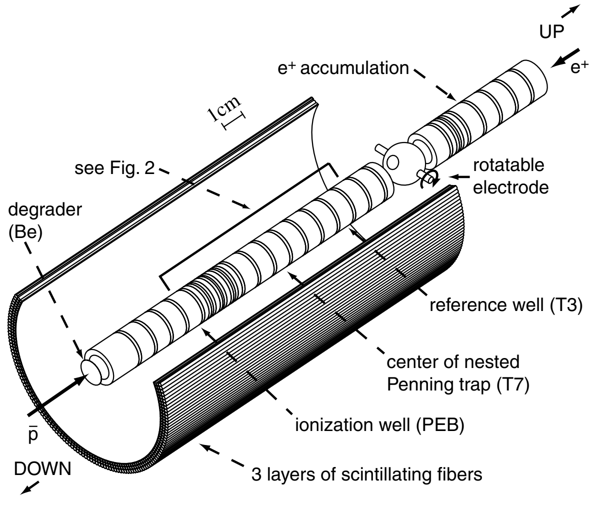

FIG. 1. Antiprotons are loaded from below (left), into the trap electrodes below the rotatable electrode. Positrons are simultaneously loaded from above (right) into the electrodes above the rotatable electrode. $\overline{\mathrm{H}}$ formation is observed within the region detailed in Fig. 2.

positronium atoms that are then ionized to accumulate e^+ [16], at the same time as the $\overline{p}$ accumulate.

The nested Penning trap [3–6] is central to $\overline{\mathrm{H}}$ production [Figs. 2(a) and 2(b)], as it was for the two earlier experiments [1,2]. The e^+ are in an inverted well at the center of a larger well for $\overline{p}$, to allow e^+ and $\overline{p}$ to be confined and interact despite their opposite charge signs. For these studies, typically 300 000 cold e^+ are located in the center well (within electrode T7). Typically 200 000 $\overline{p}$ are either divided between the two sides of the nested Penning trap (within T6 and T8) or placed in one side well.

The ionization and normalization wells [Figs. 2(a)–2(c)], to the right and left of the nested Penning trap, are carefully constructed to prevent $\overline{p}$ not bound in $\overline{\mathrm{H}}$ from being captured. A $\overline{p}$ heated out of the nested Penning trap will escape over the normalization well, unless there is a mechanism to lower the $\overline{p}$ energy within this well. To make capture harder the potential on the left of this well is lower by 3 V (on axis) than that on its right side. Getting a $\overline{p}$ into the ionization well not only requires an energy loss within the well, but also requires that the $\overline{p}$ climb a substantial potential barrier. Positron cooling keeps the $\overline{p}$ from being heated and thus makes it less likely that $\overline{p}$ will be able to pass through the ionization and normalization wells when e^+ are in the nested well.

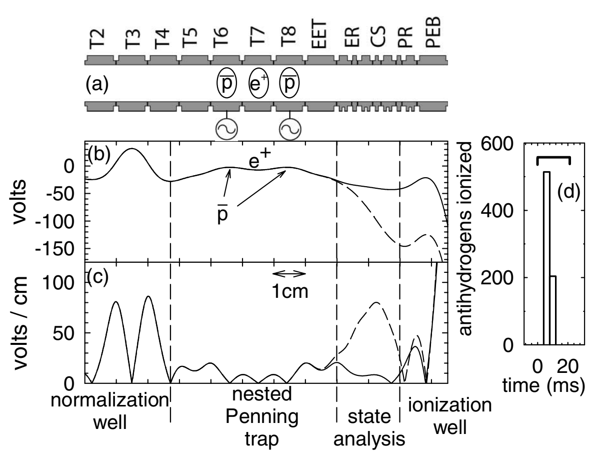

FIG. 2. Trap electrodes (a). Two values of the potential (b) and electric field magnitude (c) on axis. In a one-hour trial, 718 $\overline{p}$ from $\overline{\mathrm{H}}$ are captured in the ionization well (d).

Electric fields within the ionization and normalization wells can ionize $\overline{\mathrm{H}}$ passing through, leaving freed $\overline{p}$ in one of these wells. Figure 2(c) shows the electric field on the trap axis; in the critical state-analysis region, it varies by only about 10% off the axis. Numerical modeling of $\overline{\mathrm{H}}$ trajectories shows that $\overline{p}$ in the ionization well come from $\overline{\mathrm{H}}$ stripped by fields between 25 and 150 V/cm, while $\overline{p}$ in the normalization well come from $\overline{\mathrm{H}}$ stripped by fields between 35 and 140 V/cm.

$\overline{\mathrm{H}}$ state analysis, a central feature of this work, is done by varying the potential offset between the nested well and the ionization well. This varies the state-analyzing field that $\overline{\mathrm{H}}$ encounter on their way to the ionization well, as illustrated by two examples in Fig. 2(c). Any $\overline{\mathrm{H}}$ stripped by this field is unable to deposit its $\overline{p}$ in the ionization well, causing the measured number N of $\overline{p}$ in this well to decrease. (The stripping field in this well is stronger than are the state-analysis fields.) The number N_{norm} of $\overline{p}$ from $\overline{\mathrm{H}}$ ionization in the normalization well provides a normalization.

Crucial radiofrequency drive potentials applied alternatively to electrodes T6 or T8 [Fig. 2(a)] drive $\overline{p}$ between the sides of the nested Penning trap. During each cycle, positron cooling allows the $\overline{p}$ to settle into the opposite, undriven side well of the nested Penning trap, and some form $\overline{\mathrm{H}}$ during this cooling. Because the $\overline{p}$ are not exactly positioned at the center of these electrodes, their symmetry does not prevent driving $\overline{p}$ axial motion.

The 825 kHz frequency of a 1 V peak-to-peak drive is chosen to resonate with the calculated axial bounce frequency (Fig. 3) for $\overline{p}$ oscillating along the magnetic field direction near the axis and near the bottom of either side of the nested well. The axial bounce frequency depends on $\overline{p}$ energy, here referenced to the potential energy of a $\overline{p}$ at the center of the nested Penning trap. This frequency discontinuously halves as the $\overline{p}$ are excited out of a side well into the wider region of the nested Penning trap. The $\overline{p}$ interact with the e^+ when the $\overline{p}$ energy is between zero and -0.2 eV, the latter due to the slightly negative space charge energy of the e^+. Some optimization of the drive frequency and amplitude was done, but most of a large parameter space remains to be explored. (Another option we have used, though not for this data sample, is noise broadening the drive's frequency spectrum.)

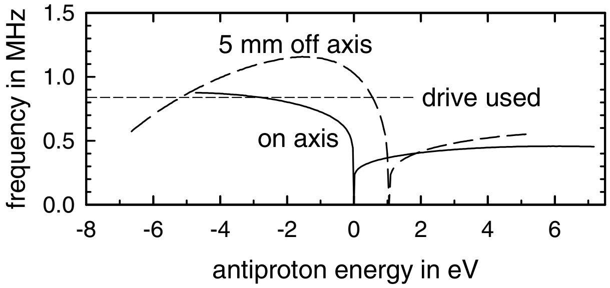

FIG. 3. Axial bounce frequency for $\bar{p}$ oscillating along the magnetic field direction in the nested Penning trap depends upon their energy, calculated with respect to their potential energy on axis at the center of the nested well. The chosen drive frequency is indicated.

We alternately drive $\bar{p}$ in one side then the other of the nested well for 10 s, with 5 s between, up to 25 times. Figure 4 shows what our detectors indicate is radial $\bar{p}$ loss from the trap. Typically we transfer most $\bar{p}$ from one side to the other, though asymmetries make it common for a constant remnant of a few ten thousands of $\bar{p}$ to remain in one side well during the whole sequence. The drive cycle timing was not optimized.

To detect $\bar{p}$ deposited in the ionization and normalization wells from $\overline{\mathrm{H}}$ ionization, we ramp down these potential wells in 20 ms, after the driving and associated particle loss are over. Ejected $\bar{p}$ annihilate upon striking electrodes, generating pions and other charged particles that produce light pulses in surrounding scintillators. The ramp is fast enough that the $1.2\ \mathrm{s}^{-1}$ cosmic ray background contributes a count in our window only 1 time in 50—essentially no background at all. Our experimentally calibrated detection efficiency [17] corresponds to 1 in 2.7 of the stored $\bar{p}$ producing a coincidence signal in surrounding scintillators. Figure 2(d) represents 718 $\bar{p}$ captured in an ionization well from $\overline{\mathrm{H}}$ ionization in a single, one-hour trial. Without e^+ in the nested well, no $\bar{p}$ from $\overline{\mathrm{H}}$ ionization are detected in the ionization well.

The observed $\overline{\mathrm{H}}$ production rate, per $\bar{p}$ and per detection solid angle, is up to a factor of 12 greater than that observed using one-time positron cooling of antiprotons [2]. The $\overline{\mathrm{H}}$ rate seems very sensitive to the number of e^+ in the nested well, unlike what was observed for the one-time cooling. This makes some sense insofar as the driving process continually heats the $\bar{p}$ and hence the e^+ they collide with. More e^+ would transfer this heat more

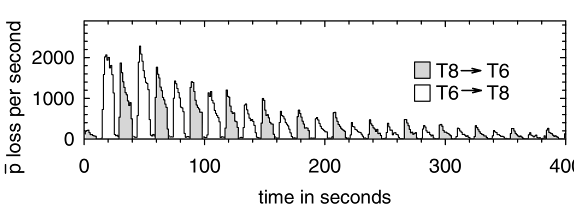

FIG. 4. Antiprotons lost while being driven from one side of the nested Penning trap to the other.

rapidly into synchrotron radiation, and increase $\bar{p}$ and e^+ overlap. Here much parameter space also remains to be explored. We presume that the $\overline{\mathrm{H}}$ are cold, insofar as the $\overline{\mathrm{H}}$ is likely made after very effective positron cooling of $\bar{p}$, but this must also be checked.

The first measured distribution of $\overline{\mathrm{H}}$ states is displayed in Fig. 5(a). The ratio (R), of the number of $\bar{p}$ from $\overline{\mathrm{H}}$ stripped in the ionization well (N) to the corresponding number in the normalization well (N_{norm}), is plotted as a function of the state-analysis field (F). The number of $\overline{\mathrm{H}}$ that survive this field decreases linearly until consistent with zero. The error bars prevent seeing curvature near this point, so we use a simple linear dependence going to zero to explore principal features. Thus dR/dF [Fig. 5(b)] is constant up to a cutoff. As many $\overline{\mathrm{H}}$ states are ionized by fields between 30 and 35 V/cm as between 55 and 60 V/cm, for example. No observed $\overline{\mathrm{H}}$ states require a stripping field greater than 62 V/cm.

It would be more satisfying to characterize the distribution of $\overline{\mathrm{H}}$ excited states by their principle quantum number n, rather than by the electric field that strips them. The first difficulty is that n is not a good quantum number in the strong $B = 5.4$ T field, though we still use n as a rough parametrization of binding energy, using $E = -13.6\ \mathrm{eV}/n^2$. Ionization likely takes place in the direction of B [18], giving some hope that it may not be strongly modified by B, but this must be investigated.

The second difficulty is that the type of Rydberg states formed determines the electric field that will ionize them, even in the absence of any magnetic field [19–21]. The field that strips a Rydberg atom entering it with principal quantum number n is given (in atomic units) by

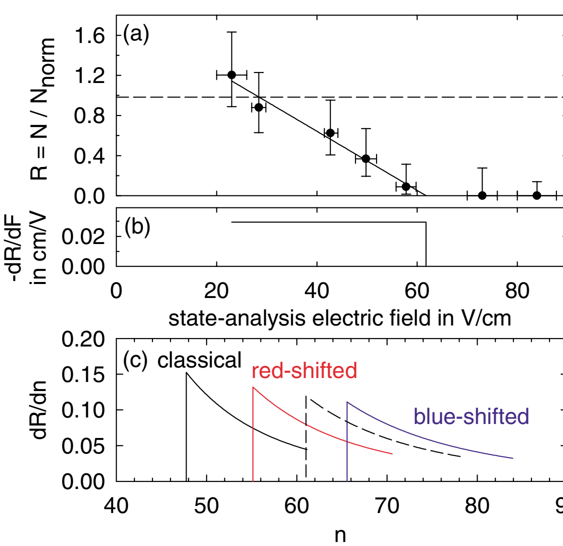

FIG. 5 (color online). (a) The ratio of ionized $\overline{\mathrm{H}}$ in ionization and normalization wells decreases linearly with state-analysis electric field F. (b) Distribution dR/dF is flat up to a cutoff. (c) The distribution $dR/dn \sim n^{-5}$ depends upon the choice of A used in Eq. (1) to relate F and n.

$$F = \frac{A}{16n^4}. \quad (1)$$

This form and the flat distribution of Fig. 5(b) indicate that the shape of the n distribution goes as $dR/dn \sim n^{-5}$.

Several examples of dR/dn are shown in Fig. 5(c) since the appropriate A for three-body recombination in a strong B field is not known. The classical "saddle point" formula, used to give some interpretation of the $\overline{\mathrm{H}}$ produced in our one-time positron cooling of antiprotons [2], has $A = 1$ and gives the lowest n distribution with $n \geq 48$. Some calculations [19,21] and hydrogen measurements [20] (all unfortunately for $B = 0$) give A values ranging between red and blue Stark-shifted values of $A \approx 1.8$ and 3.6, with a weak n dependence in some cases [19]. This latter value is also close to that for circular Rydberg states in parallel electric and magnetic fields [18]. The dashed distribution midway between the extremes with $A \approx 2.7$ gives $n \geq 65$, and the range of possibilities suggests that these n values are uncertain by at least $\pm 10\%$. Calculations of the $\overline{\mathrm{H}}$ states produced in three-body recombination, and their ionization, are clearly needed to complete the interpretation of the measured distribution of $\overline{\mathrm{H}}$ states.

Finally, further enhancements of $\overline{\mathrm{H}}$ production seem likely with optimizations and variations on our method of arranging for many cycles of positron cooling of antiprotons. One variation would be to simultaneously drive $\overline{p}$ on both sides of the nested Penning trap. Another would be to lift $\overline{p}$ from the bottom of the nested well in a potential "bucket" for launching back into the nested Penning trap.

In conclusion, the observed $\overline{\mathrm{H}}$ production per $\overline{p}$ injected into the ATRAP apparatus is encouragingly high when $\overline{p}$ are driven into collisions with cold e^+ in a nested Penning trap. The distribution of $\overline{\mathrm{H}}$ states has been measured for the first time with an analyzing electric field in a separate region between where the $\overline{\mathrm{H}}$ are produced and detected. The observed distribution dR/dF is constant as a function of the state-analysis field, up to cutoff, and implications for the distribution in principal quantum number are explored. The Rydberg states and high production rate are consistent with a three-body recombination mechanism [3,12,13].

The high $\overline{\mathrm{H}}$ production rate suggests the possibility to devise a way to deexcite Rydberg atoms with a range of binding energies and still get enough atoms for trapping and spectroscopy. Some temporary confinement of these highly polarizable states may be possible, but conventional trapping awaits deexcitation to the ground state, whereupon a goal is to superimpose a magnetic trap for $\overline{\mathrm{H}}$ with the Penning traps needed for its $\overline{p}$ and e^+ ingredients [22].

We are grateful to CERN, its PS Division, and the AD team for delivering the 5.3 MeV antiprotons. This work was supported by the NSF, AFOSR, the ONR of the U.S., the BMBF, MPG, and FZ-J of Germany, and the NSERC, CRC, and PREA of Canada.

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Search and Discovery

Second CERN Group Produces Cold Atoms of Antihydrogen

A new experiment, by CERN's ATRAP collaboration, introduces a technique for determining the quantum state in which antihydrogen atoms are formed.

Two collatorations at CERN have been pursuing a long-term goal: to make precision tests of how an atom of antimatter might differ from its ordinary-matter counterpart. An antihydrogen atom (consisting of a positron bound to an antiproton) might, for example, fall at a slightly different rate than a hydrogen atom. Or the lowest-lying states of the positron might have slightly different energies than those of the electron in hydrogen. If a precision test indicated that either hypothesis were true, it would shatter a very basic tenet of physics. Different rates of fall would challenge predictions of general relativity, and different energy levels would violate the invariance of physics under the simultaneous operations of charge conjugation, time reversal, and parity inversion.

To conduct such precision tests, of course, one must first form cold atoms of antihydrogen--not an easy task. A step in this direction was the demonstration by CERN's ATRAP collaboration that antiprotons could be put into the same trap (a so-called nested Penning trap[1]) as the positrons and cooled by those positrons.[2] Following that lead, a second CERN group--the ATHENA collaboration--reported in September[3] the detection of cold antihydrogen (see Physics Today, November 2002, page 17). The ATRAP collaboration has now weighed in with its own results.[4,5]

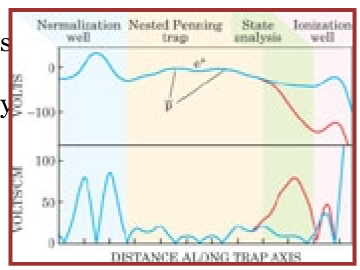
Not only did ATRAP researchers produce

Also this month
Second CERN Group Produces Cold Atoms of Antihydrogen
A Little Extra Weight Goes a Long Way
Isotope Ratio Measurements Firm Up Knowledge of Earth's Formation

and detect more antihydrogen atoms than were seen by the ATHENA team, but they used a detection method that tells them about the quantum state in which the atoms were formed. The evidence gathered by ATRAP collaborators confirmed their expectation that the H- atoms formed in the experiment occupy highly excited Rydberg states. The next challenge is to come up with a way to deexcite the atoms to the ground state, as required for making precision measurements.

ATRAP, which is led by Gerald Gabrielse of Harvard University, is a collaboration of researchers from Harvard, the Research Center Jülich in Germany, the Max Planck Institute for Quantum Optics in Garching, Germany, the University of Munich in Germany, and York University in Toronto, Canada.

Detecting antihydrogen



Figure

Both CERN collaborations working independently used similar means to nudge the antiprotons and positrons together to form H- atoms, but they had very different approaches to detecting them. To make antihydrogen, each group took antiprotons from CERN's Antiproton Decelerator, further slowed them, and trapped them with a configuration of electric fields. Each group also trapped and cooled positrons from the radioactive decay of a sodium isotope. And, in each experiment, the separately trapped antiprotons and positrons were then loaded into nested Penning traps.

In such a trap, electric and magnetic fields confine the antiprotons and positrons to a cylindrical region, with separate potential wells confining the two types of particles. In general, the positrons are confined to a region in the center, along the cylinder's axis, and antiprotons bounce back and forth longitudinally through the positron cloud (see the figure on page 16). The cold positrons further cool the antiprotons (to 15 K in the ATHENA setup and to 4 K in the ATRAP experiment). As the antiprotons

ATRAP experiment). As the antiprotons pass through the region of positrons, some H- atoms are formed.

To detect antihydrogen, ATHENA collaborators looked for the particles that emanate when an H- atom hits the nearest wall; upon impact, the positron and antiproton composing the antiatom annihilate their matter counterparts. The specific signature sought by ATHENA researchers was the observation of a pair of oppositely moving photons (from positron annihilation) in coincidence with the sighting of several pions (from antiproton destruction).

By contrast, the ATRAP team used an electric field to ionize any H- atoms that traveled some distance away from the production region along the trap axis. Such ionization presumably yielded antiprotons, which ATRAP collaborators collected and counted in what they call the ionization trap, as shown in the figure.[2]

Commenting on the different detection methods, Steven Rolston of NIST in Gaithersburg, Maryland, notes that the technique used by the ATHENA group is reminiscent of particle physics, and the detection scheme adopted by the ATRAP team is in the style of atomic physics.

Gabrielse said that he and his ATRAP colleagues made sure that they could get an antiproton in their ionization trap only if a neutral H- atom escaped their nested Penning trap. Any antiprotons that might have escaped the nested Penning trap should have too much energy to be stopped in the ionization trap. Indeed, the experimenters accumulated antiprotons only when positrons were present in the Penning trap. "We were elated but not surprised to see that the signal was indeed background free," Gabrielse said.

To increase the yield of H- atoms as a function of the number of antiprotons, ATRAP team members increased the number of times the antiprotons went back and forth through the positron region. They did that by using a radiofrequency drive to heat the antiprotons stored on either side of the 4-K positron region. They would heat first one side, then the other, in a periodic manner.

Determining the quantum state

There are two ways in which an antiproton and a positron might combine to form an H-atom: In three-body recombination, an antiproton and two positrons interact to yield an antihydrogen atom and a leftover positron that carries away the extra energy and momentum. In radiative recombination, an antiproton merges with just one positron, and a photon carries off the additional energy and momentum. Three-body recombination tends to produce atoms in Rydberg states, which take a long time to cascade down to the ground state

No one knew exactly which one of those two antihydrogen production processes would dominate in the ATHENA and ATRAP experiments and hence what quantum states would be formed. To get an idea of the quantum state of the H- atoms, ATRAP researchers added another feature to their experimental setup: a state-analysis region, through which an H- atom must pass on its way to the ionization region, as seen in the figure .

In the state-analysis region, the researchers apply an electric field, shown by the red curve, to ionize the H- atoms. When ionization occurs, the resulting antiprotons will escape and the number of antiprotons snared in the ionization trap will decrease.

Gabrielse and company varied the electric field in the state-analysis region and recorded the drop in the numbers of antiprotons accumulated. They found the drop by comparing the numbers of antiprotons in the ionization trap with those in a normalization trap on the other side of the Penning trap, where there is no state-analysis region.

The strength of the field that ionizes an atom is a measure of the energy level occupied by the positron: The more tightly bound a positron, the higher the ionization field must be. Thus the observed decrease in the numbers of accumulated antiprotons is a measure of the number of H- atoms with a given quantum number. It's hard to translate the measured ionization potential exactly into the principal quantum number *n*. Still, the experimenters estimate that all the atoms they formed were Rydberg atoms, with values of n greater than about 50.

The ATRAP collaborators saw no evidence for lower-lying states. They found that the numbers of ionized H- atoms declined as they raised the field to higher values. Beyond an electric field of 62 V/cm, they saw no further decreases. The experimenters took that as evidence that they were not seeing any tightly bound states. In future experiments, researchers might look for lower-lying antihydrogen states more directly by exciting them with a laser to states that can be ionized.

Whereas the ATRAP researchers have determined that their experiment forms Rydberg atoms, the same conclusion does not necessarily hold for the ATHENA setup, in part because ATHENA produces H- atoms at higher temperatures. Rolf Landua, ATHENA's spokesman, said that his team now has evidence that three-body recombination is not the dominant process in their experiment.

Rydberg atoms

No one has yet calculated the properties of Rydberg atoms moving randomly in magnetic fields as high as those found in a Penning trap. However, the ATRAP team's measurements may well motivate some new calculations. One complication, says Hossein Sadeghpour of the Harvard-Smithsonian Center for Astrophysics, is that one can't separate the center-of-mass motion from the internal coordinates, as can be done with many other systems. Thomas Gallagher of the University of Virginia notes that "using field ionization as a detection technique has subtleties even without a magnetic field. Understanding it with one presents quite a challenge."

One goal of such Rydberg calculations will be to guide the experimenters as they devise techniques to bring the highly excited atoms quickly down to their ground states, where the precision experiments must be performed. Left to their own devices, Rydberg atoms tend to take a long time to decay, during which time they might be lost from their trap. Daniel Kleppner of MIT notes that, to date, those studying Rydberg atoms have been concerned with how to put them in the higher states; they now face the reverse problem.

Gabrielse said that in ATRAP's next run, which begins in June 2003, his group will try to bring the Rydberg H- atoms to lower energy levels with laser deexcitation methods. He and his collaborators also hope to test ways to select specific Rydberg states. Furthermore, they also need to figure out a way to store the neutral particles.

Barbara Goss Levi

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ANTIMATTER

Antihydrogen Rivals Enter the Stretch

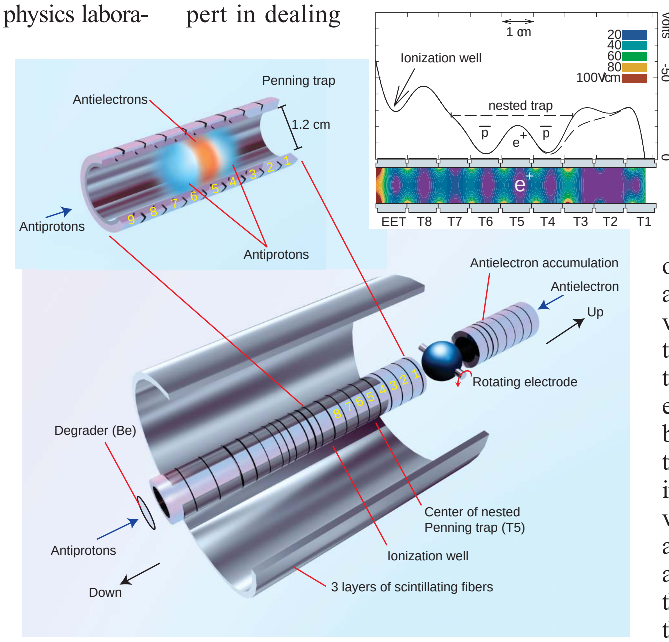
Two teams are vying to probe the properties of mirror-image atoms—a race in which key ideas of physics are at stake

Antimatter, the fuel of countless science-fiction spacecraft, has catapulted into the front pages twice in the past few months. Two rival teams are hot on the trail of antihydrogen, the antimatter doppelgänger of the simplest element, hydrogen. Known as ATHENA and ATRAP, they use similar techniques, nearly identical equipment, and the same particle beam, an antiproton factory at CERN, the European particle physics laboratory near Geneva. Within a month, each announced that it had created tens of thousands of "antiatoms" cold and slow-moving enough to be studied. The results marked the first surge forward in a race to measure antihydrogen's spectrum—a discovery that could rattle the foundations of physics and will likely net a Nobel Prize for whichever team gets there first. Not surprisingly, the competition is intense.

Physicists have known for decades that every bit of matter—whether it be an elementary particle like an electron or composite object like a proton—should have an antimatter equivalent with identical mass and equal but opposite charge. Yet almost all of the known mass in the universe seems to be made out of matter rather than antimatter. Some underlying asymmetry must have led the cosmos to "prefer" matter to antimatter. To learn more, physicists around the world have been waiting for someone to trap and study antihydrogen: the simplest antimatter "element," an antielectron bound to an antiproton in a combination that nobody has ever spotted in nature.

The ATHENA and ATRAP teams are fighting to be the first to analyze antihydrogen's properties. Their goal is to make and then capture enough to measure its spectrum, the wavelengths of light it absorbs. Scientists think that antihydrogen's spectrum should be identical to hydrogen's. If it's not, a key principle in physics known as CPT symmetry will have to be discarded, forcing a drastic revision of physicists' understanding of subatomic particles.

As the two groups close in on that prize, the rivalry is heating up. "There's been some friction between them, and I'm regretful that there has been," says Daniel Kleppner, a physicist at the Massachusetts Institute of Technology and an expert in dealing with cold hydrogen. "It may diminish each other's pleasure of discovery." But Kleppner stresses that the tension shouldn't detract from the real story: the production of significant amounts of cold, slow antihydrogen. "The fact that both groups have gotten antihydrogen is a major accomplishment," he says. "The friction shouldn't deflect from their achievements."



Going negative. "Antiatom" traps use sandwiched potentials (inset) to bring oppositely charged particles together.

ILLUSTRATION: CAMERON SLAYDEN/*SCIENCE*; GRAPH SOURCE: ADAPTED FROM GABRIELSE *ET AL*., *PHYSICAL REVIEW LETTERS*

Until a few months ago, the smart money was on ATRAP. Its leader, Gerald Gabrielse, a physicist at Harvard University, was the recognized expert in the field of trapping and cooling antiprotons. "He was the first person to do atomic physics with antiprotons, he figured out how to cool them, and he did a marvelous measurement of the [lack of] mass difference between antiprotons and protons," Kleppner says. "So I view him as having opened up the field." Others on the 15-member ATRAP team had worked on the experiment that first made hot antihydrogen at CERN in 1995. The new team quickly started racing toward cold antihydrogen production.

But ATRAP was not the only horse in the race. ATHENA, led by CERN's Jeffrey Hangst, had access to the same beamline, the Antiproton Decelerator (AD) at CERN, which takes protons created at near the speed of light down to about 10% of that speed. Drawing on years of experiments with AD's predecessor, LEAR, both groups settled on electromagnetic bottles known as Penning traps to cool antiprotons down to about 4 kelvin, confine them with antielectrons, and induce the two to combine.

ATHENA and ATRAP follow the same basic recipe for antimatter. Each gets its antiprotons from AD and its antielectrons from a radioactive sodium isotope that emits the particles as it decays. Each captures the antiprotons, cools them to a few kelvin, and shoots them and the antielectrons into opposite ends of a trap where they can mix.

The traps—meter-long cylinders that corral the particles with electromagnetic fields—face a daunting challenge: Because antiprotons and antielectrons have opposite charges, a potential that captures antielectrons repels antiprotons and vice versa. That makes it difficult to build a single trap that can hold both of them, because a trap that appears like a valley to an antielectron looks like a hill to the antiprotons. To bring the particles together, both teams use a trap within a trap—in effect, two hills framing a valley (from the antielectrons' point of view) or two valleys flanking a hill (from the antiprotons' point of view) (see figure). When an antielectron binds to an antiproton (something that occurs with only a handful of the thousands of cold antiprotons in each shot), the resulting neutral antiatom can no longer be easily controlled by electric or magnetic fields. It escapes the trap and floats away.

That's where the big differences start. To tell that they've created antihydrogen, the ATHENA physicists look for gamma rays that are produced when an antihydrogen atom is annihilated by collisions with ordinary matter. By subtracting the background gamma rays from their total count, they can estimate the number of antiatoms. Gabrielse's ATRAP team, by contrast, lets the untrapped neutral antihydrogens float into an additional trap, which tears apart the antihydrogen atom. The team then counts the liberated antiprotons as they annihilate on contact with ordinary matter. As a bonus, the ionization trap also yields information about how tightly the antielectron is bound to the antiproton.

The race for the spectrum began with a false start last year, when ATRAP succeeded in cooling antiprotons together with antielectrons but couldn't prove that it had made the particles combine. This September, the underdog ATHENA drew first blood in the duel for antihydrogen. It announced in *Nature* that it had produced an estimated 50,000 slow-moving antihydrogens (*Science*, 20 September, p. 1979).

"ATRAP was leading the way in technology over time. ATRAP was always ahead," says Steve Rolston, a physicist at the National Institute of Standards and Technology in Gaithersburg, Maryland. "Coming in second was a shock." Gabrielse acknowledges that he was taken aback. "It surprised me when they got the paper published, but such is life," he says. At first, he expressed some reservations about ATHENA's results—it can be easy to mistake background events for antiatoms—but he concedes that ATHENA probably created antihydrogen. "They're honest people and did a fairly careful job," he says. "Right now, I presume they have seen antihydrogen atoms."

But Gabrielse was poised to strike back. In October, ATRAP released a paper that will be published in *Physical Review Letters* that goes beyond ATHENA's work: Not only does it claim the production of about 170,000 cold antihydrogen atoms, but it begins to analyze their properties. With its ionizing trap, Gabrielse's team confirmed predictions that the antielectrons would occupy a high "orbit" around their antiprotons, placing the antihydrogens in a loosely bound, high-energy "excited" state.

This high-energy state complicates the task of taking antihydrogen's spectrum. An antihydrogen in a highly excited state won't absorb the wavelengths of light that physicists are so interested in. To get much information, physicists have to coax the antiatoms back down to their ground state—a slow process compared with the seconds it takes to mix the antiprotons and antielectrons. Thus, the teams will have to trap a lot of antihydrogen for minutes, hours, or even longer before they can get a reasonable spectrum. Existing equipment might not be up to the job, says Rolf Landua, a physicist on the ATHENA team.

Another problem is that the teams' source of antiprotons has just dried up. The current run of CERN's beamline just ended, so both teams will have to wait until next year to resume the race. And the budget problems at CERN (*Science*, 29 March, p. 2341) will interfere with their scramble to collect antihydrogen. "[AD] will be shut down for 1 year, which is a huge disappointment," says Gabrielse. "Without antiprotons, it's hard to make progress."

For now, frozen neck and neck, the rivals can only plan their next round of experiments, fine-tune their equipment, and wait. Says Gabrielse: "I would give a lot for one more week of beam time." –CHARLES SEIFE

GRADUATE STUDENT UNIONS

Labor Seeks Fertile Ground On Ivy-Covered Campuses

Graduate student unions aren't a new phenomenon at state universities. But their presence at elite private schools is raising the ante for scientists

CAMBRIDGE, MASSACHUSETTS—When graduate students at Cornell University in Ithaca, New York, overwhelmingly rejected joining the United Auto Workers (UAW) last month, they scotched what would have been only the second student union at a private U.S. university. A week after the 24 October vote, UAW organizer Joan Moriarty, a Ph.D. candidate in labor economics, still shakes with anger as she recounts the bruising 18-month battle for the hearts and minds of her 2300 colleagues, two-thirds of them in science and engineering fields. Fierce opposition from Cornell's president, a vocal antiunion student group, and reports that some faculty members had warned their grad students that a "yes" vote could jeopardize their careers swung the vote against the union, she believes. However, others say that organizers erred by pushing for a vote before they were ready and hooking up with UAW. "It was a setback, not a defeat," she asserts, tearfully vowing to continue the fight.

Image not available for online use.

Stand up and be counted. A federal labor official explains the rules before the recent vote by graduate students at Cornell University.

CREDIT: PETER NORLANDER/CORNELL DAILY SUN

Whatever happens at Cornell, Moriarty won't be alone. Similar organizing efforts are being waged on dozens of U.S. campuses. No longer exclusively blue-collar, unions also represent some 40,000 graduate students at 27 universities around the country. Unlike their counterparts in many countries, U.S. graduate students often carry heavy teaching loads—spending 20 hours or more a week on duties only tenuously related to their graduate training. Their unhappiness over pay, benefits, and job-related working conditions—as well as nonfinancial issues such as inadequate grievance procedures and career counseling—has been red meat for union organizers. Although teaching assistants still dominate most union bargaining units, research assistants (RAs) are becoming more prominent in the wake of a 2000 ruling by the National Labor Relations Board that RAs perform "work" apart from pursuing their degree requirements.

Ironically, there is a dearth of rigorous, academic research on how graduate student unions affect academia, notes Elaine Bernard, a labor educator who heads the Labor and Worklife program at Harvard University. Earlier this month, her program joined with a network of labor economists to put on a 2-day meeting here to explore scientific workforce issues, including the rise of graduate student unions and the status of postdocs, a traditionally downtrodden class of researchers who have begun to improve their status through cooperative rather than confrontational tactics (see sidebar). The network is funded by the New York City–based Alfred P. Sloan Foundation, which has a long-standing interest in the health of the U.S. scientific work force.

What's at stake. The first graduate student union was established at the University of Wisconsin in 1969. Most have been formed in the last decade, however—and none without a fight. The early conflicts took place at public universities, which are governed by state labor laws that are often more receptive to unionization. The battleground has now spread to private institutions. One of the longest running, and most bitter, fights is being waged at Yale University, where administrators have steadfastly refused to recognize the AFL-CIO–affiliated Graduate Employees and Students Organization (GESO) nature physicsportal

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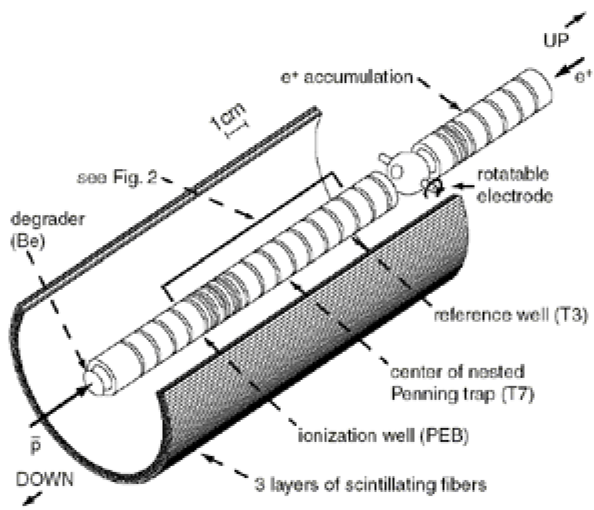
• collections
• highlights
• news
• looking back
• problem page
• magazine
• biology
• renaissance physicist
information
• meetings
• links
• about the portal
services
• e-alert
• help
• feedback
• search
large text
send to a friend

To the heart of the antimatter

The recent production of 50,000 atoms of cold antihydrogen — the antimatter equivalent of hydrogen — by the ATHENA collaboration marked an important milestone in high-energy physics (see On the anti-factory floor). But this work, carried out at CERN, the European laboratory for particle physics near Geneva, was only the beginning. In this week's *Physical Review Letters*, Gerald Gabrielse and his colleagues in the ATRAP collaboration, also working at CERN, report production of a record-breaking 170,000 antihydrogen atoms using a technique that may offer insights into the anti-atoms' structure.



The apparatus used to form antihydrogen. Antiprotons fed into the bottom of the apparatus and positrons fed into the top are confined in a nested Penning trap at the centre. Collisions between these particles cool the antiprotons allowing atoms of antihydrogen to form.

The production and confinement of antihydrogen atoms offers physicists the chance to subject the standard model of high-energy physics to one of its most rigorous tests yet. According to this model, antihydrogen atoms should have exactly the same internal electronic states as normal hydrogen. This can be checked by comparing the emission and absorption spectra of antihydrogen to those of hydrogen — a particularly stringent test as the spectra for hydrogen are known to an accuracy of a few parts per 10^{14} for the transition between the ground and the first excited state.

Many of the techniques used by ATHENA to produce cold antihydrogen were developed by ATRAP. Key to both groups' strategies is the 'nested Penning trap'. Antihydrogen is generated from collisions between positrons and antiprotons, but a single electrostatic trap — or Penning trap — cannot be used to hold these particles together because they have opposite charges. This can be overcome by nesting a positron trap within a larger antiproton trap. While contained within the trap, collisions between the relatively hot antiprotons and the cold gas of positrons cause the former to cool, and eventually leads to their coalescence to form antihydrogen.

In their latest study, Gabrielse *et al*. significantly increased both the production and detection of cold antihydrogen atoms compared with previous work. Once formed, neutral antihydrogen atoms can escape the confining potential in which they were created, causing them to drift throughout the apparatus. By using a field-ionization technique to strip the positrons from these drifting anti-atoms, and then trapping and counting the resulting antiprotons, the authors unambiguously observed the creation of 657 antihydrogen atoms. Assuming a collection efficiency of 11%, this implies the creation of an astounding 170,000 antihydrogen atoms — more than the total of all antihydrogen atoms previously reported.

More significantly, the authors' field-ionization technique could give the first glimpse of the atomic states of antihydrogen. By varying the field required to ionize an antihydrogen atom, the team hopes to obtain information about the anti-atom's internal states as well as getting a better idea of what it will take to de-excite the anti-atom to its ground state for subsequent spectroscopic studies.

Whatever the results of future antihydrogen experiments, the outcome is likely to be a win-win situation for physicists. Positive results would represent yet another triumph for one of the most successful physical models ever devised. But perhaps more tantalizing, any deviations from the standard model's predictions would revolutionize high-energy physics and lead to further breakthroughs in our understanding of the fundamental nature of the Universe.

See also: On the anti-factory floor.

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of its States
G. GABRIELSE, N. S. BOWDEN, P. OXLEY, A. SPECK, C. H. STORRY, J. N. TAN, M.WESSELS, D. GRZONKA, W. OELERT, G. SCHEPERS, T. SEFZICK, J.WALZ, H. PITTNER, T.W. HÄNSCH & E. A. HESSELS (ATRAP Collaboration)
A background-free observation of cold antihydrogen atoms is made using field ionization followed by antiproton storage, a detection method that provides the first experimental information about antihydrogen atomic states. More antihydrogen atoms can be field ionized in an hour than all the antimatter atoms that have been previously reported, and the production rate per incident high energy antiproton is higher than ever observed. The high rate and the high Rydberg states suggest that the antihydrogen is formed via three-body recombination.
Physical Review Letters **89,** 213401 (31 October 2002)
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