

COMPARING THE ANTIPROTON AND PROTON, AND OPENING THE WAY TO COLD ANTIHYDROGEN

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Abstract: Our TRAP collaboration has developed and demonstrated slowing, trapping, and electron-cooling techniques that enable antiproton storage in thermal equilibrium at 4.2 K. This is an average energy that is more than 10^{10} times lower than the energy of any previously available antiprotons. Months-long confinement of a single antiproton, at a background pressure $< 5 \times 10^{-17}$ torr, and nondestructive detection of the radio signal from a single trapped antiproton, made it possible to show that the charge-to-mass ratios of the antiproton and proton differ in magnitude by < 9 parts in

10^{11} . This 90 parts per trillion comparison is nearly a million times more accurate than previous comparisons, and is the most stringent test of PCT invariance with a baryon system by a similar amount. The availability of extremely cold antiprotons makes it possible to pursue the production of antihydrogen that is cold enough to trap for precise laser spectroscopy. The closest approach to cold antihydrogen to date is our simultaneous confinement of 4.2 K antiprotons and positrons. All cold antiproton experiments so far were carried out at the CERN Laboratory with antiprotons coming from its Low Energy Antiproton Ring (LEAR). This unique facility has now closed. Future antihydrogen experiments will be pursued at the new Antiproton Decelerator ring at CERN, which was constructed for this purpose. Using the techniques developed by TRAP, antiprotons will be accumulated within traps rather than in storage rings, thereby reducing the operating expenses to CERN.

I. World's Lower Energy Antiprotons by a Factor of 10^{10}

Stored antiprotons are now available in thermal equilibrium at 4.2 K. This is an energy that is 10^{10} times lower (Fig. 1) than the lowest energy antiprotons available before our TRAP Collaboration (Table 1) developed and demonstrated new techniques over the last decade. Our extremely cold antiprotons made possible a series of three comparisons of the charge-to-mass ratio of the antiproton and proton that improved this comparison by nearly a factor of 10^6 , the most precise test of PCT invariance with baryons by approximately this factor. The extremely cold antiprotons, and a method to accumulate them in a trap, make it possible to pursue the production and study of cold antiprotons at the new Antiproton Decelerator facility at the CERN laboratory.

Antiprotons are the antimatter counterparts of protons, the familiar constituents of ordinary matter (along with electrons and neutrons). Antiprotons occur naturally only as the very occasional products of a collision between a high energy cosmic ray and an atom in the atmosphere. Although believed to be stable particles, the naturally occurring antiprotons nonetheless live for only a short time. A single collision between an antiproton and any proton in ordinary matter can annihilate both particles. The antiproton and proton cease to be and a variety of lighter particles (mostly pions) are formed. Antiprotons can thus be stored only in a container that has no walls and essentially no ordinary matter within.

Starting in 1955, in the Bevatron storage ring at Berkeley, usable numbers of antiproton have been produced and studied using giant storage rings within which antiprotons travel at speeds close to that of light. Protons of extremely high energy are made to collide with ordinary matter. In a small fraction of these collisions, antiprotons are formed, which can be directed into large circular storage rings. Technological improvements allowed the CERN Laboratory in Geneva to accumulate much larger

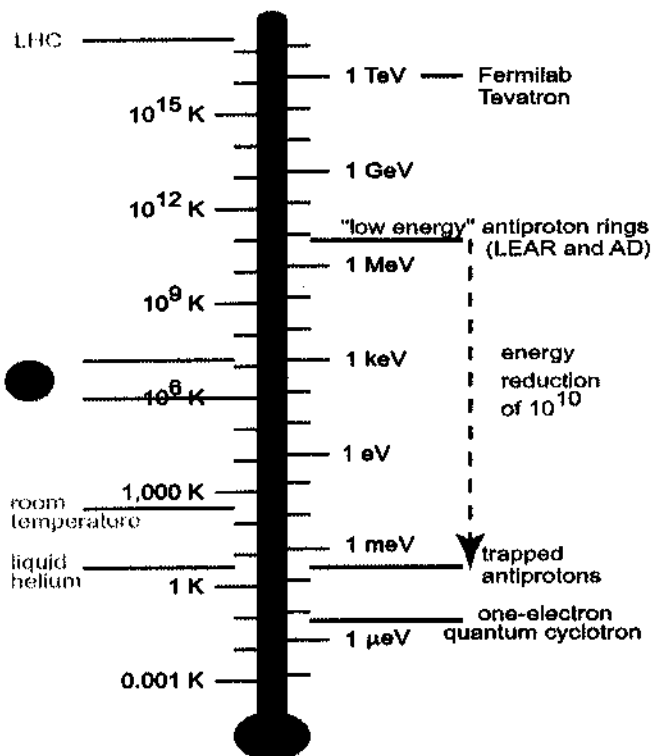


FIG. 1. Our trapped antiprotons are the lowest energy antiprotons in the world by more than a factor of 10^{10} . The vast energy scale for charged particles is represented on a logarithmic "thermometer."

TABLE I
TRAP COLLABORATION: CERN PS-196

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numbers of antiprotons that were collided with protons so that the short-lived W and Z particles could be observed and studied. At Fermilab in Illinois, higher energy collisions between antiprotons and protons are being investigated to learn about the top quark.

Such high energies and velocities are desirable for experiments in which antiprotons are made to collide with other particles. However, new experiments became possible when the CERN Laboratory began operating the Low Energy Antiproton Ring (LEAR) in 1982. It has a modest circumference of only 79 m (much smaller than the 27 km circumference for the LEP ring at CERN). LEAR slowed and cooled antiprotons to an energy of 6 MeV, a speed that is approximately 0.1 of the speed of light, and sent them to various particle and nuclear physics experiments.

The "Low" in Low Energy Antiproton Ring was initially appropriate insofar as at the time these antiprotons were much lower in energy than any other antiprotons available in the world. However, the energy of antiprotons in LEAR was nonetheless much higher than the average energy of particles in the sun. Compared to the much lower energy we needed to do precision mass spectroscopy of antiprotons, and to prepare for antihydrogen that is cold enough to be trapped for high precision laser spectroscopy, the LEAR energy was very high indeed — by at least a factor of 10^{10} .

The new techniques developed by TRAP, listed in what follows, allow slowing and cooling of antiprotons to energies that are lower by the required factor of 10^{10} . The slowed and cooled antiprotons reside within a small volume (less than 1 mm^3) of an ion trap in a nearly perfect vacuum (better than 5×10^{-17} torr). Their average kinetic energy is so low, $< 1 \text{ MeV}$, that temperature units are often used. The energy "thermometer" of Fig. 1 contrasts the energy of antiprotons and protons in various giant storage rings at the top with LEAR energies in the middle. Towards the bottom, 10^{10} times lower in energy than is possible in LEAR, is the new low energy frontier at only 4° above absolute zero (4 K). Even lower antiproton temperatures should be possible as illustrated by the 70 mK temperatures we recently realized with trapped electrons in a similar ion trap (Peil and Gabrielse, 1999).

1. *Slowing in matter to very low energy.* Some of the 6 MeV antiprotons from LEAR slowed below 3 keV while passing through a thin window of matter. The fraction was initially measured during a 24-h beam time allocation in 1986 (Gabrielse *et al.*, 1986, 1989a).
2. *Trapping antiprotons.* Antiprotons slowed below 3 keV are captured while they are within the electrodes of a Penning trap (Brown and Gabrielse, 1986) by the sudden application of a 3-kV trapping potential (Gabrielse *et al.*, 1986). This was first demonstrated in a 24-h beam time allocation in 1986.

3. *Electron cooling of trapped antiprotons.* The trapped antiproton, with keV energies, cooled via collisions with simultaneously trapped electrons (Gabielse *et al.*, 1989b). The electrons radiated synchrotron radiation to return to thermal equilibrium with their 4.2 K surroundings.
4. *Long-term storage of 4.2 K antiprotons monitored nondestructively.* We held antiprotons for months, monitoring them via the currents induced in surrounding electrodes by their motion, without loss of antiprotons (Gabielse *et al.*, 1990).
5. *A pressure $< 5 \times 10^{-17}$ torr.* Antiprotons remained trapped for months without any detectable loss, establishing a 3.4 month limit for our antiproton storage time and for antiproton decay into all channels. Calculated cross sections allow us to convert this storage time limit to the pressure limit already mentioned here (Gabielse *et al.*, 1990).
6. *Nondestructive monitoring of one trapped \bar{p} (or a \bar{p} and H^- together).* Good control and detection sensitivity with one or two trapped particles allowed the comparisons of q/m for the antiproton and proton to be improved by almost a factor of one million (Gabielse *et al.*, 1990, 1995, 1999b).

These techniques were reported in *Physical Review Letters* and in the *Rapid Communications of Physical Review*, as indicated. A semipopular account was presented in *Scientific American* (Gabielse, 1992).

A. FIRST SLOWING AND TRAPPING OF ANTIPROTONS

The apparatus used to cool antiprotons to low temperatures and to measure accurately their charge-to-mass ratio falls in the realm of "table top" experiments in that its size would allow it to be mostly located on the top of a table. A big complication is that the table top must be located at a large particle physics facility capable of supplying antiprotons.

My trip to Fermilab in 1981 did not succeed in generating much interest in low-energy antiproton experiments. An intense focus on the primary Fermilab mission of studying TeV collisions between protons and antiproton left no room for the low energy experiments envisioned, even though a small operating ring (used for cooling studies) might have been adapted for this purpose. In 1985, Bill Kells of Fermilab came to work with me for one year, bringing the news that the small storage ring was shut down and pieces were being shipped to other laboratories. We thus turned our attention to mounting an experiment in Geneva, since the unique LEAR facility at the CERN laboratory was the only place in the world that could slow antiprotons to the MeV energies that a table top apparatus could accept. Hartmut Kalinowsky of the University of Mainz in Germany joined

forces with us, as did Tom Trainor of the University of Washington in Seattle.

Initially there was some skepticism at CERN about our proposals to slow antiprotons in matter, capture them in an ion trap and cool them within the ion trap via collisions with cold electrons in the same trap. These unproven techniques were very different from the normal high-energy collision experiments done at CERN. Moreover, one of our physics goals was in direct competition with an experiment in which CERN had already invested a great deal. There was also concern because we had no financial support while making our proposal. Funding agencies in the United States, with limited resources in tough economic times, were cautious about a large new program to be carried out at CERN but which did not yet have CERN approval. CERN and the funding agencies were not reassured by the fact that none of us had regular academic positions with tenure. Fortunately, first the Atomic Physics Division of the National Science Foundation, then the Air Force Office of Scientific Research and the National Bureau of Standards (now National Institute of Standards and Technology (NIST)) decided jointly to fund the quest for low-energy antiprotons. Only after the experiments succeeded did we learn that an NSF consensus found the opportunity too good to pass up despite an estimated likelihood of success in trapping cold antiprotons of $< 20\%$.

Eventually CERN allowed us 24 h access to LEAR antiprotons to demonstrate that it really was possible to slow antiprotons from MeV energies down to < 3 keV. Figure 2a shows the gas cells and time-of-flight apparatus, and Fig. 2b shows the number of antiprotons and protons transmitted through the gas cells and degrader as the gas mixture was changed to tune the energy of these particles.

When we were able to demonstrate that enough low-energy antiprotons were available for trapping in 1986, we were given a second 24-h access to antiprotons two months later, to demonstrate that we could capture the slowed antiprotons. This demonstration experiment took place before there was time to purchase very much modern equipment. An ancient superconducting magnet was loaned to us by the University of Mainz. An ion trap was constructed in one day from glass-to-metal seals of unknown origin that were found abandoned in glass blower's drawer. After testing in our own laboratory, we shipped the apparatus by air owing to time pressure and the delicate nature of the helium Dewar we had constructed. After the Dewar arrived broken in Geneva, we learned that our "air" shipment actually traveled across Europe in trucks of unknown suspension quality. It is hard to forget aiming a misbehaving hand torch at "borrowed" hard solder within a Dewar that dangled from a rope slung over a beam in a CERN hallway.

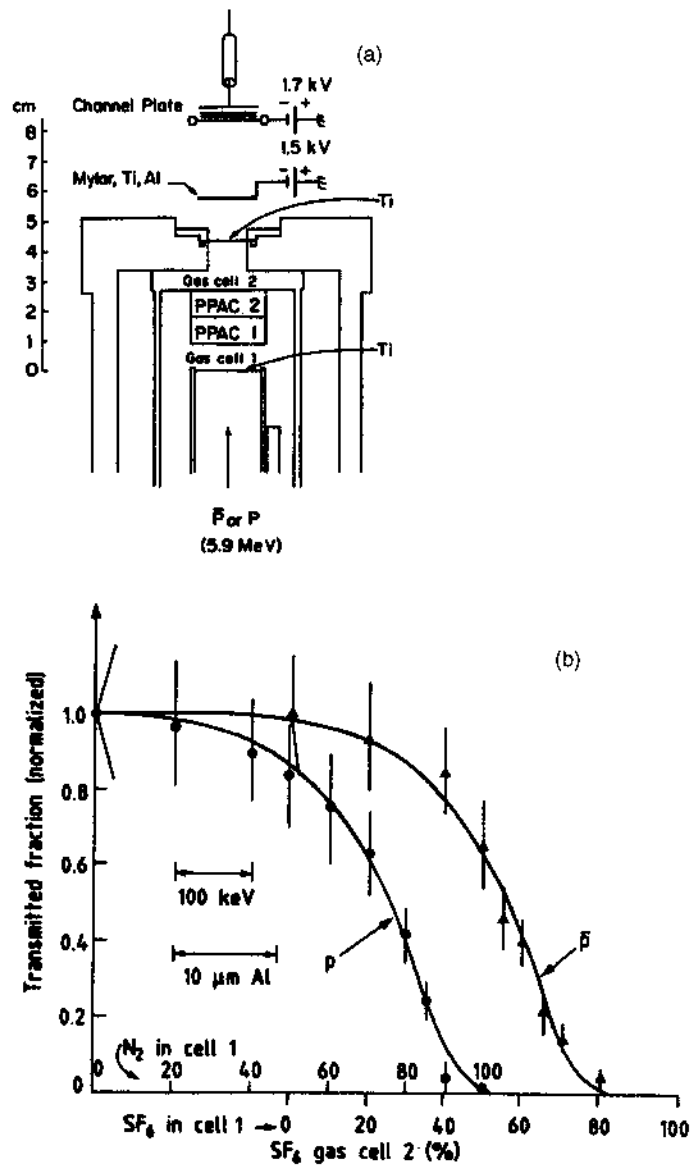


FIG. 2. (a) Gas cells and time-of-flight apparatus used to measure the number of antiprotons slowed to keV energies in a degrader. (b) Number of transmitted antiprotons as a function of the gas mixture varied to decrease the energy of the antiprotons incident on the degrader window. (Taken from Gabrielse *et al.*, 1989a.)

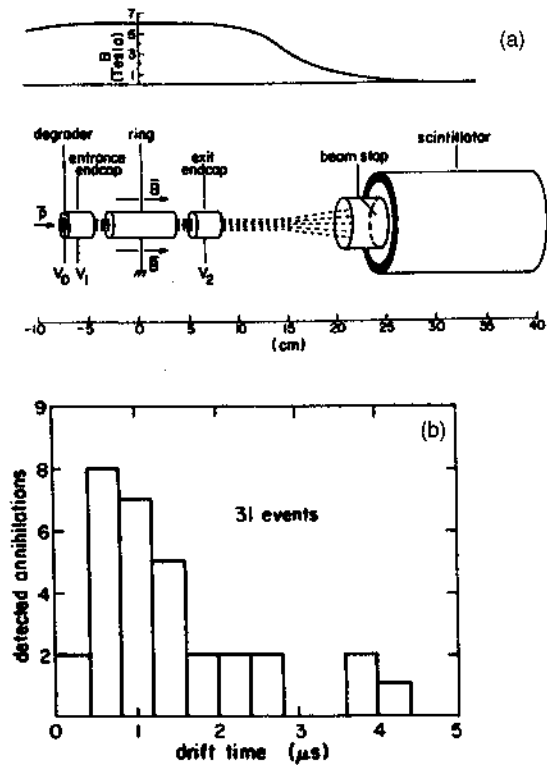


FIG. 3. (a) Scale outline of the apparatus that first trapped antiprotons. (b) Annihilation signals from the first trapped antiprotons when they were released from the trap after being held for 1000 s. (Taken from Gabrielse *et al.*, 1986.)

The repaired apparatus (Fig. 3a) was ready several days before antiprotons were scheduled to arrive at noon on Friday. Feverish computer programming was continuing ("just one half hour more of Basic") to read out information about attempted antiproton captures in real time. Then, late Thursday evening, disaster struck. Routine tests, done dozens of times before, revealed that we could no longer apply high voltages to our trap electrodes without causing an arc inside the part of the Dewar that was cooled to 4 K. It was 12 h before the antiprotons were scheduled to arrive and the apparatus had never been warmed to room temperature and then cooled back to 4 K in less than several days. Half of our team went to bed convinced that we had failed.

Given CERN's ambivalence about the feasibility of the proposed experiments, a failure in this test experiment would clearly be a major setback, so a repair had to be attempted. As the cold apparatus was prematurely opened, water condensed on it and streamed out, despite the hot air directed in from three industrial-strength hair dryers. The breakdown point was located and fresh copper cables installed to handle the high voltages. After much mopping of water, drying and cleaning, we reassembled the apparatus during the night and began cooling by 10 a.m., Friday. We informed the LEAR control room that we would indeed be ready for our antiproton test by shortly after noon.

Our euphoria was short-lived. Their reply indicated that CERN was not yet ready to deliver antiproton to us. Such particles were indeed available in the large Antiproton Accumulator (AA) storage ring at CERN, but the "kicker" device used to extract antiprotons from this ring had broken. It was most likely that we would leave CERN without receiving antiprotons. I explained the urgency of the situation (how far we had come, the stakes involved etc.), then stumbled off to bed exhausted and discouraged. The test experiment appeared doomed for some time, since LEAR was soon scheduled to be shut down for more than 1 year.

Several hours later I was awakened. An accelerator magician at CERN had managed to make a backup "kicker" work. Soon LEAR was ready to try to send us intense pulses of antiprotons (about 10^8) in short bursts (200 ns). This "fast extraction" mode of operation was new at LEAR. The operators counted "five, four, three, two, one," in various versions of English, and then pushed a newly installed green button with a loud "go." After several hours of adjusting the timing electronics, we started to see clear and unmistakable signals that indicated we were able to trap antiprotons in our ion trap at energies <3 keV. The emotional roller coaster that this antiproton test experiment had become ended on a pronounced high. The LEAR operators and physicists from other experiments crowded around during the countdown. Applause broke out any time the histogram (see Fig. 3b) on the computer monitor indicated that antiprotons had been trapped and stored. A few antiprotons were held as long as 20 min, thereby establishing the feasibility of the proposed measurements.

B. CAPTURING AND COOLING ANTIPROTONS

This success turned CERN ambivalence into CERN enthusiasm. A connection to LEAR was constructed and dedicated to these experiments while LEAR was shut down for 1 year. Our new apparatus, installed in the fall of 1988, included a state-of-the-art superconducting solenoid and a carefully constructed ion trap suited to precise measurement of the antiproton mass.

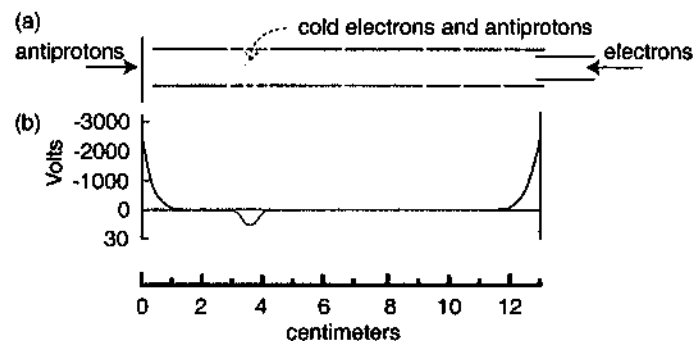


FIG. 4. (a) Outline of trap electrode surfaces and the location of cold trapped particles. (b) Typical potential well on axis.

The electrodes of the particle trap (Fig. 4a) were a stack of gold plated copper rings to which appropriate voltages could be applied. The electrodes resided within a 6-tesla magnetic field directed along the symmetry axis of the cylinders and produced by the superconducting solenoid.

Charged particles make circular orbits around the direction of a magnetic field. Antiprotons and electrons in the trap thus orbit in circular trajectories rather than traveling radially outward to hit the trap electrodes. Before antiprotons are allowed into the trap, electrons are loaded into the small region indicated by the representation of the axial potential wells of the trap in Fig. 5. Internally generated electrons sent through the trap strike the flat plate at the left and dislodge adsorbed gas atoms. Other electrons collide with some of these atoms within the small region in such a way as to produce low-energy electrons in this location. Positive tens of volts on the electrodes at this location attract the negative electrons, keeping them from exiting at either end. The electrons in circular orbits about the magnetic field direction rapidly radiate their energy (typically in 0.1 s) and cool to the temperature of the surrounding electrodes near 4 K.

The 6-MeV antiprotons in an intense pulse from LEAR crash through the flat plate electrode at the left of the trap, losing energy via collisions within the goldplated aluminum degrader. Approximately one in a few thousand of the antiprotons emerge with an energy (along the axis of the trap) of <3 keV. These can possibly be trapped using the voltages described here. Antiprotons that emerge from the aluminum with higher energy are not turned around by the modest -3 kV being applied to the electrode at the far right, so are annihilated upon hitting this electrode. Others lose too much energy by collisions within the aluminum, slow to a stop within the plate, and eventually annihilate. The flat degrader electrode is kept slightly

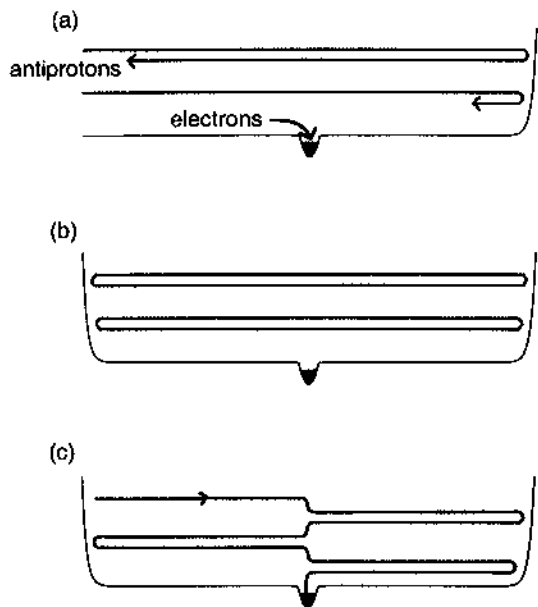


FIG. 5. (a) Cold trapped electrons in a small central trap well await the introduction of a pulse of hot antiprotons into the long "half well." (b) When the maximum number of antiprotons are in the trap volume a high voltage is applied to complete the well. (c) On a much longer time scale hot antiprotons cool via collisions with cold electrons and eventually join the electrons in the small trap well.

positive while the antiprotons are passing through to keep secondary electrons from leaving the degrader and filling the trap. After the antiprotons enter the trap, but before they return to the entrance plate, this potential is changed to -3 kV to prevent them from striking the plate upon their return. To shut this door before the rapidly moving antiprotons can escape, this potential is changed in 20 ns. Figure 6 shows the relative number of antiprotons trapped as a function of the time that the door is shut and Fig. 7 shows how the number of antiprotons trapped is optimized by tuning the energy of the antiprotons incident on the degrader window (by changing the gas mixture).

Captured antiprotons oscillate back and forth along the 12-cm length of the trap, with energies ranging between 0 and 3 keV, passing through the cold, trapped electrons. Just as a heavy bowling ball would eventually be slowed by collisions with light ping-pong balls, the antiprotons cool (in < 100 s time we typically reserve for cooling) to thermal equilibrium with

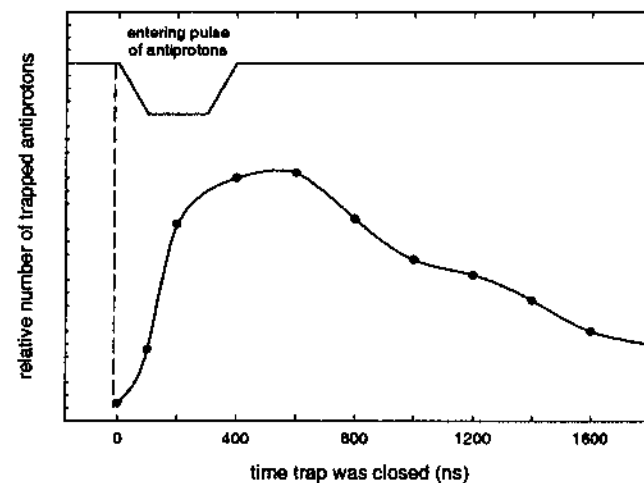


FIG. 6. Number of antiprotons trapped as a function of the time at which the trap is closed (below), with the injected antiproton pulse shown (above) on the same time scale.

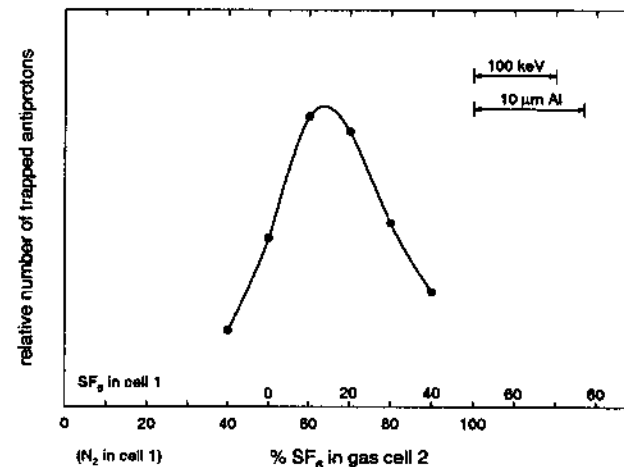


FIG. 7. The energy of antiprotons that arrive at our apparatus at 6 MeV is tuned downward (by varying the amount of SF₆ in the beam path) to maximize the number of trapped antiprotons.

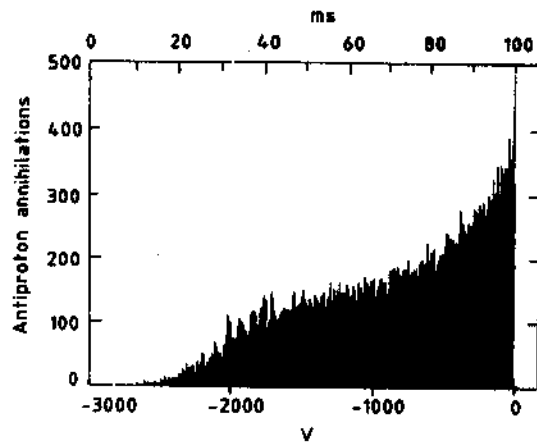


FIG. 8. Energy spectrum for hot trapped antiprotons. (Taken from Gabrielse *et al.*, 1989b.)

the trapped electrons at 4 K. Cooled antiprotons now reside in the same small region of the trap as do the electrons and their energy is 10^{10} times lower than the energy of the antiprotons that came from LEAR. Figure 8 shows the trapped antiproton energy distribution before electron cooling. The number of annihilations is measured as the potential on one end of the long well is reduced. After electron cooling the greatly narrowed spectra of Fig. 9 are observed. The energy width of these spectra is only an upper limit insofar as the space charge of the low-energy antiprotons allows some of them to escape at a well depth that is higher than their kinetic energy. The cooling process is remarkably efficient in that upwards of 95% of the antiprotons in the long trap are so cooled, as illustrated in Fig. 10.

As many \bar{p} as will fit, limited by space charge to about 0.4 million, end up in the small inner, harmonic well with approximately 10^7 cooling electrons. We trap up to 0.6 million antiprotons from a single LEAR pulse in inner and outer traps together (Fig. 11), with an efficiency (compared to the number of antiprotons measured to leave LEAR) shown in Fig. 12.

To selectively expel the cooling electrons they are heated by driving them at frequencies that correspond to their preferred oscillation frequencies. When the voltages on the neighboring electrodes are lowered for a very short time the hot electrons leak out of the trap. The cold, heavy antiprotons remain and are subsequently cooled using cold resistors connected between various nearby electrodes. Residual antiproton motions induce currents through these resistors. Power dissipated in the resistors is thereby extracted from the antiproton motion, cooling the antiprotons into thermal equilibrium with the resistors, which are near 4 K.

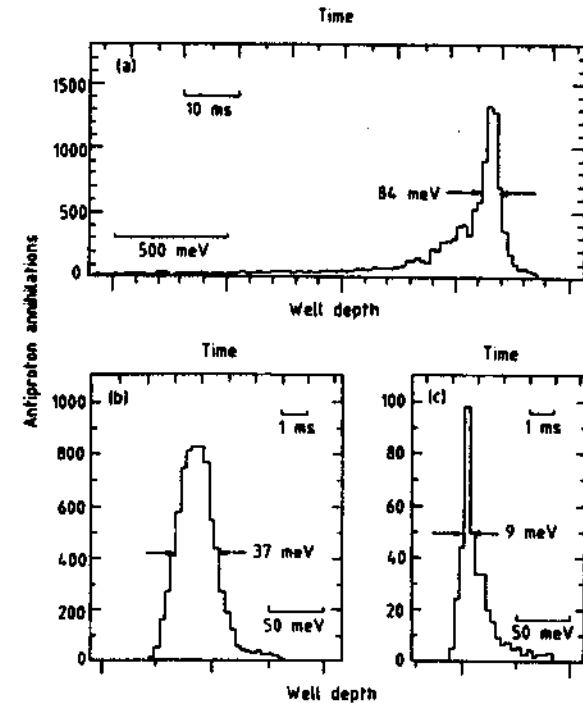


FIG. 9. Energy spectra for decreasing numbers of cold antiprotons. (Taken from Gabrielse *et al.*, 1989b.)

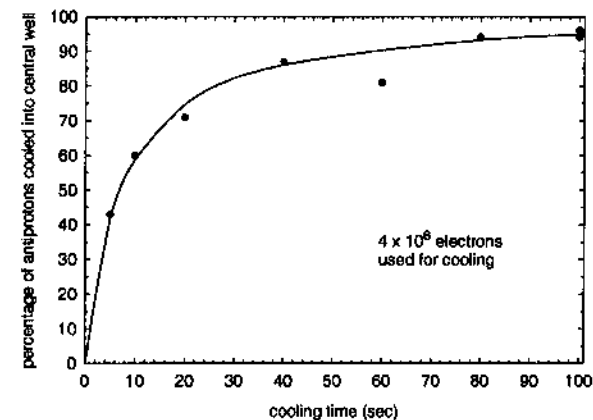


FIG. 10. Fraction of antiprotons cooled into the center harmonic well as a function of cooling time with 4×10^6 cooling electrons.

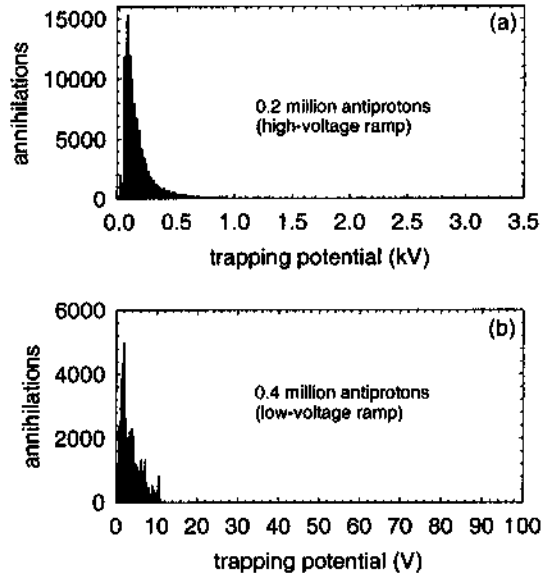


FIG. 11. Energy spectrum of 0.6 million antiprotons trapped from a single 250-ns pulse of antiprotons from LEAR. Approximately 0.4 million (below) were able to fit in the small central trap well with the electrons that cooled them. An additional 0.2 million were cooled somewhat but remained in the long well (above). (Taken from Gabrielse *et al.*, 1999.)

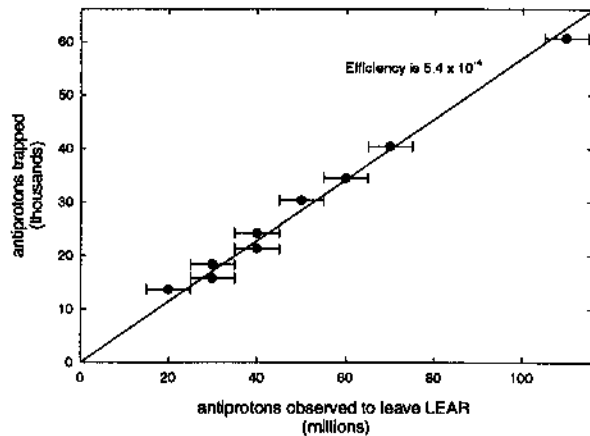


FIG. 12. Number of trapped antiprotons versus the number of 6 MeV antiprotons sent down our beamline as measured by the LEAR beam monitor; gives an efficiency of 5×10^{-4} .

When only one antiproton is needed for q/m measurements we slowly reduce the well depth of the small trap to let all but one antiproton escape. We monitor the cyclotron signal (we will discuss this presently). When only a few antiprotons remain we can resolve the signals from each antiproton because of the relativistic shift in their cyclotron frequencies.

C. VACUUM BETTER THAN 5×10^{-17} TORR

It seems that we can store the cold antiprotons indefinitely. In one trial we held approximately 10^3 antiprotons for about 2 months before deliberately ejecting them (Gabrielse *et al.*, 1990). We actually observed no antiproton loss at all, but imprecision in our knowledge of the number of antiprotons initially loaded into the trap limits the lifetime we can set to

$$\tau_{\bar{p}} > 3.4 \text{ months} \tag{1}$$

Despite the much lower energies (and hence much higher annihilation cross sections), this lifetime limit is longer than directly observed for high-energy antiprotons in storage rings for decays into all channels. Based upon calculated cross sections (Morgan and Hughes, 1970), our containment lifetime limit given here requires a background gas density $< 100 \text{ atoms/cm}^3$. For an ideal gas at 4.2 K this corresponds to a pressure $< 5 \times 10^{-17}$ torr. The low pressure is attained by cooling the trap and its sealed container to 4.2 K.

D. STACKING ANTIPROTONS: MAKING THE ANTIPROTON DECELERATOR (AD) POSSIBLE

We typically captured a pulse of antiprotons from LEAR and let it cool via its interaction with 4.2 K electrons over the following 100 s. For charge-to-mass measurements we would then eject all but one antiproton. To facilitate the production and study of cold antihydrogen, however, the largest possible number of cold, trapped antiprotons is desired. To this end we demonstrated that once captured antiprotons had been cooled into an inner potential well it was possible to capture additional pulses of antiprotons from LEAR right over top of the first (Gabrielse *et al.*, 1990). After the capture and cooling process represented in Fig. 5 is completed, one simply repeats it as many times as desired. The number of trapped antiprotons thus increases over what can be captured in a single pulse.

The TRAP demonstration of “antiproton stacking” in a trap is the foundation upon which the new antiproton decelerator is based. Antiprotons delivered from LEAR were initially captured in the antiproton

collector ring (ACOL), accumulated in the antiproton accumulator ring (AA), then slowed and cooled within the low energy antiproton ring (LEAR) and sent to our trap. When we demonstrated that antiprotons could instead be accumulated in a small trap, and much more inexpensively than in the large storage rings, the CERN management decided to shut down two of the three rings to save expenses. (The alternative was to entirely discontinue all low-energy antiproton physics.) The ACOL Ring was substantially modified to make the new antiproton decelerator (AD).

The good news is that the experimental efforts to produce and precisely study cold antihydrogen can continue. The bad news is that the new facility brings additional challenges. To obtain the same number of cold, trapped antiprotons that we captured from LEAR in 250 ns will require us to accumulate (i.e., stack) antiprotons from the AD for an hour or more.

E. TRANSPORTING TRAPPED ANTIPROTONS

From our initial proposal at CERN, we stressed that our Penning trap was an intrinsically portable device. Trapped antiprotons could certainly be transported within our Penning trap if ever there was a good reason to do so. Although the compelling reason never emerged, we were nonetheless often asked about this possibility. Finally, in 1993 we used the opportunity of the delivery to our Harvard laboratory of a new superconducting solenoid constructed in California to make an experimental demonstration. In a Penning trap apparatus that was essentially identical to our antiproton apparatus, we transported stored electrons from California to Nebraska, then from Nebraska to Cambridge (see Fig. 13) (Tseng and Gabrielse, 1993). (The tale of an avoidable adventure in a Nebraska truck stop will not be retold here.) Electrons were used because they were much more readily available in California and Nebraska, but there is no doubt whatever that antiprotons could just as easily be transported if there had been a good reason.

F. LATER DUPLICATION OF TRAP TECHNIQUES BY OTHERS

For many years, the techniques to obtain cold antiprotons, all of which were developed and demonstrated by TRAP, were used exclusively by TRAP. More recently, some of these techniques were duplicated by the PS-200 collaboration, which has since developed into ATHENA. The PS-200 motivation was to measure the gravitational acceleration of antiprotons using a time-of-flight technique. Most of a decade was spent pursuing this goal but unfortunately this effort was not successful. As one would expect, the gravitational force of the earth on an antiproton is simply

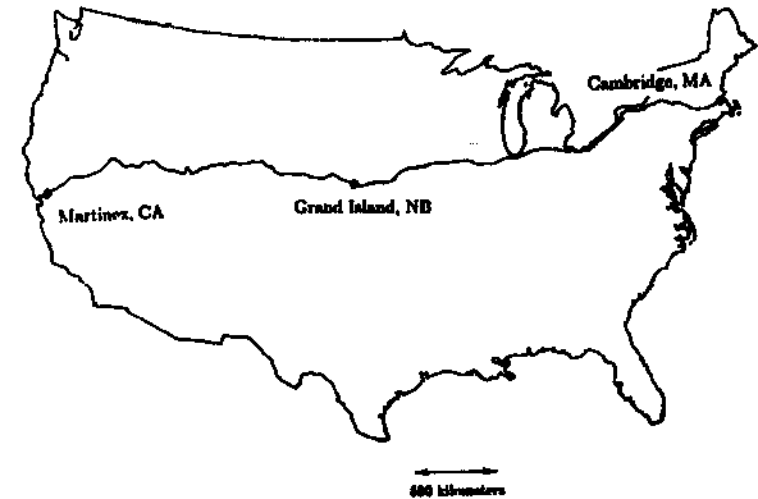


FIG. 13. Trapped electrons were transported from California to Nebraska, and then from Nebraska to Massachusetts. (Taken from Tseng and Gabrielse, 1993.)

too small compared to the electric force from stray charges in the apparatus.

The conditional approval of PS-200 offered antiprotons only after the desired gravitational sensitivity in the time-of-flight measurements was demonstrated with negative ions. When the end of the LEAR program was in sight, however, permission was granted to try to duplicate the TRAP techniques for trapping and cooling antiprotons despite the absence of the promised demonstration. The trap used (Holzscheiter *et al.*, 1996) was a larger version of the open endcap cylindrical trap used by TRAP (Gabrielse *et al.*, 1989c). A higher trapping potential was also used. Up to a million antiprotons were trapped at the same time. The vacuum was not so good as that demonstrated by TRAP due to higher trap temperatures and the presence of warm surfaces in the vacuum system, and the antiproton storage time was of the order of 10^3 s rather than months. Antiprotons were eventually cooled with electrons—but not to 4 K.

The only new feature of the PS-200 measurements was the surprising claim that antiprotons stored in poor vacuum annihilate much less rapidly than expected (Holzscheiter *et al.*, 1996). However, very little quantitative study was done and the actual vacuum within the trapping volume was estimated rather than measured. Hopefully, this surprise will eventually be tested under more controlled conditions.

G. LOWER TEMPERATURE ANTIPROTONS ARE COMING

For some years single component plasmas of elementary particles have been studied at temperatures down to 4 K. We have now managed to cool stored electrons down to 70 mK and below. So far, only one trapped electron (at a time) has been studied in detail at this low temperature, though there is no reason to expect any difficulties with larger numbers.

Quantum jumps between Fock states of a 1-electron oscillator reveal the quantum limit of a cyclotron (Peil and Gabrielse, 1999). With a surrounding cavity inhibiting synchrotron radiation 140-fold, the jumps show a 13 s Fock state lifetime, and a cyclotron in thermal equilibrium with 1.6–4.2 K blackbody photons. These disappear by 80 mK, a temperature $50 \times$ lower than previously achieved with an isolated elementary particle. The cyclotron stays in its ground state until a resonant photon is injected. A quantum cyclotron offers a new route to measuring the electron magnetic moment and the fine structure constant.

Although the demonstration was done with trapped electrons, there is every reason to believe that the same apparatus would also cool antiprotons to the same 70 mK temperature. Our ATRAP collaboration, an expanded version of TRAP formed to study cold antihydrogen, plans to pursue this option.

II. Million-Fold Improved Comparison of Antiproton and Proton

Our proposal to improve the comparison of the charge-to-mass ratio of the antiproton and proton to 1 part in 10^9 was a surprise at CERN. One reason was that the proposed techniques were very unfamiliar at CERN. Another was that CERN had already invested in an experimental program with similar goals (CERN PS-189), employing a large Smith-type mass spectrometer. (Unfortunately, the angular acceptance of the spectrometer was so small that it was never able to make any antiproton measurements.) Over several years we were able to achieve the accuracy we had proposed and even to do an order of magnitude better. Our series of three mass measurements (Gabrielse *et al.*, 1990, 1995, 1999) began as soon as we produced 4.2 K antiprotons and eventually improved the comparison of antiproton and proton by approximately 10^6 . Figure 14 shows how comparison of the antiproton and proton improved in time, starting with the first observation of the antiproton, and concluding with the three measurements by TRAP.

A. TESTING PCT INVARIANCE

The P in PCT stands for a parity transformation. Suppose we do a certain experiment and measure a certain outcome. As we do the experiment, we

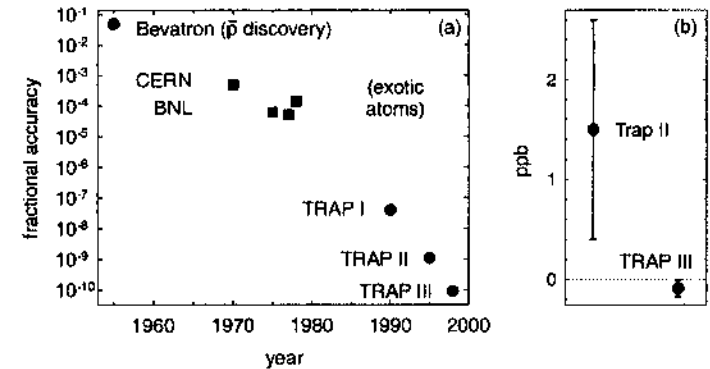


FIG. 14. (a) Accuracy in comparisons of \bar{p} and p . (b) The measured difference between $|g/m|$ for \bar{p} and p (TRAP III) is improved more than ten-fold. (Taken from Gabrielse *et al.*, 1999.)

also watch what the experiment and outcome look like in a mirror. We then build apparatus and carry out a second experiment that is identical to the mirror image of the first. If our reality is invariant under parity transformations P then we should obtain the outcome seen in the mirror for the second experiment. Until 1956 it was universally believed that reality was invariant under parity transformations. Then Lee and Yang noted that this basic tenet of physicists' faith had not been tested for weak interactions—those interactions between particles that are responsible for beta decay of nuclei. Shortly after, Wu and collaborators, and then several other experimental groups in rapid succession, showed in fact that experiments and mirror image experiments produced strikingly different results when weak interactions were involved. The widespread faith that reality was invariant under parity transformations had clearly been misplaced.

A new faith, that our reality was invariant under PC transformations, rapidly replaced the discredited notion. The "C" stands for a charge conjugation transformation, which for our purposes is a transformation in which particles are turned into their antiparticles. To test whether reality is invariant under PC transformations, a mirror image experiment is constructed as described here but this time all the particles within it are also changed into antiparticles. It was widely believed that these two different experiments could not be distinguished by their outcomes until Cronin and Fitch surprised everyone by using kaon particles to explicitly demonstrate that our reality is not invariant under PC transformations. The experiment has been repeated by different groups in different locations and related measurements are still being pursued.

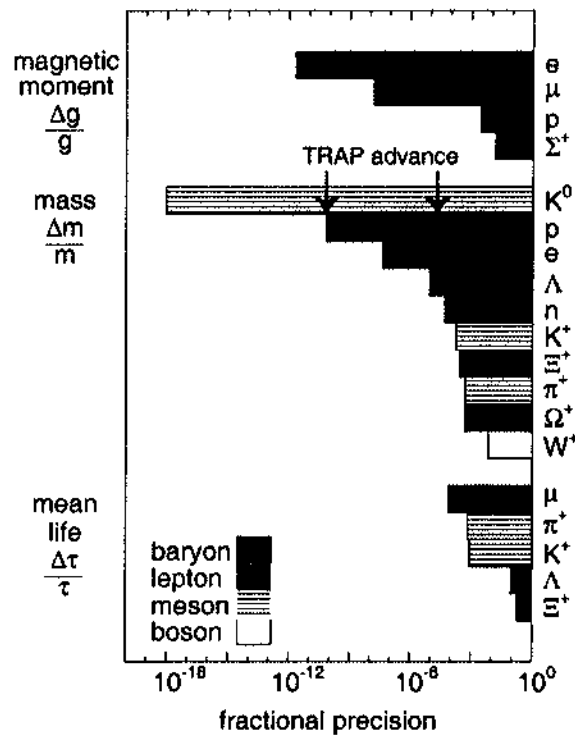


FIG. 15. Comparison of the accuracy of baryon, lepton and meson PCT tests

Now most physicists believe that reality is instead invariant under PCT transformations, the “T” standing for a time reversal transformation. The PCT invariance seems more well-founded insofar as theorists find it virtually impossible to construct a reasonable theory that violates this invariance. To experimentally test for PCT invariance, one again compares the outcomes of two experiments. This time one makes a movie of the goings on in a mirror image experiment in which the particles are switched to antiparticles. The second experiment is constructed to mimic what one sees in the movie when the movie is run backwards (i.e., when “time is reversed”).

In practice, the cyclotron oscillation frequencies of a proton and an antiproton oscillating in the same magnetic field would be identically the same if reality is invariant under PCT transformations. The antiproton-proton frequency comparisons discussed in what follows thus test whether reality is PCT invariant and establish that any departures from this

invariance must be smaller than the experimental error bars. This comparison is by far the most precise test of PCT invariance done with baryons, particles made of three quarks or three antiquarks. The antiproton-to-proton charge-to-mass ratio comparison thus joins an experiment with kaons (made of a quark and an antiquark) and a comparison of the magnetic moment of an electron and positron as one of the most precise experimental tests of whether our reality is invariant under PCT transformations. The improved comparison of the antiproton and proton which we discuss next strengthens our belief in PCT invariance.

The various tests of PCT made by comparing the measured properties of particles and antiparticles are represented in Fig. 15. The stable particles and antiparticles in these tests come in several varieties that are important to distinguish. The proton (antiproton) is a baryon (antibaryon). The proton (antiproton) is composed of three quarks (antiquarks) bound together. The K mesons, like all meson particles and antiparticles, are instead composed of a quark and an antiquark bound together. The third variety of particle is the lepton; the electron and the positron are one example of lepton particle and antiparticle. Leptons are not made of quarks. In fact, so far as we know, leptons are perfect point particles. No experiment has yet been devised that gives evidence of any internal structure at all. It seems crucial to test PCT invariance in a sensitive way for at least one meson system, one baryon system, and one lepton system. The comparison of q/m for the antiproton and protons, discussed next, is the most sensitive test of PCT invariance with a baryon system by approximately a factor of million. The proposed comparison of the hydrogen and antihydrogen, discussed later, is of great interest in that it promises to give a much more sensitive test of PCT invariance with leptons and baryons.

B. COMPARING CYCLOTRON FREQUENCIES

The first measurement with extremely cold antiprotons was a greatly improved comparison of the charge-to-mass ratios of the antiproton and the proton. Figure 14 represents previous comparisons (with different techniques) along with the series of three TRAP measurements. The basic ideas for TRAP comparisons are illustrated in Figs. 16 and 17. An antiproton, proton, or H^- ion makes a circular orbit in a plane perpendicular to the magnetic field direction as shown. The orbit angular frequency ω_c is simply related to the charge of the particle q , its mass m , and the strength of the magnetic field B , by

$$\omega_c = \frac{q}{m} B$$

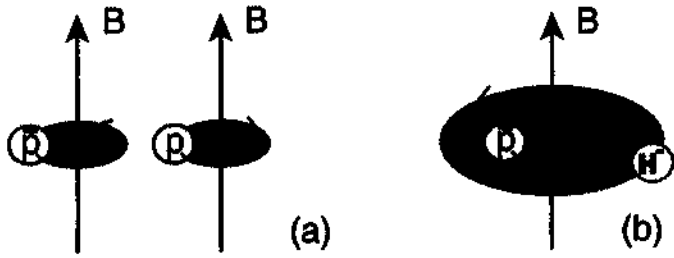


FIG. 16. (a) For TRAP I and TRAP II, antiprotons and protons are alternated in the trap. (b) For TRAP III, a simultaneously confined antiproton and H^- ion were interchanged between larger and smaller concentric orbits.

In the strong magnetic field we use, antiprotons, protons and H^- ions make approximately 90 million revolutions. We detect the 90-MHz signal (Fig. 19) induced across the RLC circuit attached to the electrodes of the trap (Fig. 19) using a refined version of an FM radio receiver, and measure the oscillation frequency. The points in Fig. 14b indicate the amount that the ratio of measured antiproton and proton cyclotron frequencies differs from 1. If the magnetic field does not change between measurements of ω_c for the antiprotons and protons, the ratio of cyclotron frequencies can be interpreted as a ratio of q/m .

In reality, an antiproton confined in a Penning trap follows the slightly more complicated orbits represented in Fig. 18. The small circular oscillation is the cyclotron motion discussed in the preceding except that the oscillation frequency is slightly modified by the trap to ω'_c . This cyclotron motion is superimposed on another circular orbit perpendicular to the magnetic field, called magnetron motion, at a much lower frequency ω_m . In addition, the antiproton oscillates up and down along the direction of the

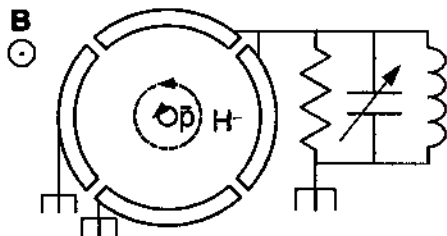


FIG. 17. The cyclotron motion induces a detectable voltage across an RLC circuit attached to a 4-segment ring. (Taken from Gabrielse *et al.*, 1999.)

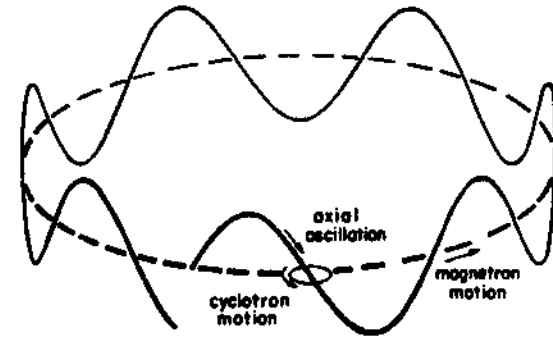


FIG. 18. Superimposed cyclotron, axial and magnetron orbit of a particle in a perfect Penning trap. (Taken from Brown and Gabrielse 1986.)

magnetic field at the axial frequency ω_z . The desired cyclotron frequency ω_c is deduced from the three measurable frequencies ω'_c , ω_z , and ω_m using an invariance theorem which Lowell Brown and I discovered (Brown and Gabrielse, 1982),

$$\omega_c^2 = \omega_c'^2 + \omega_z^2 + \omega_m^2 \quad (2)$$

Much of the experimental effort goes into understanding and/or eliminating any imperfection in our apparatus that could change the measured frequencies even slightly. Nonetheless, each of the three measurable frequencies is slightly shifted from the ideal — by a misaligned magnetic field for example. Fortunately, the invariance theorem holds even when the three measurable frequencies are shifted by this misalignment and the other largest sources of frequency shifts. Depending on the accuracy of the measurements, approximations to this general expression can sometimes be used.

It is essential that the magnetic field B not change between the time the proton frequencies are measured and the antiproton frequencies are measured. This is challenging in an accelerator environment in which magnetic fields in the accelerator rings are being changed dramatically as often as every couple of seconds. One important aid for all three of our measurements is a superconducting solenoid that not only makes the strong magnetic field but also senses when this field fluctuates and cancels the fluctuation at the location of our trapped particles. This invention (Gabrielse *et al.*, 1988, 1991) is now patented (Gabrielse and Tan, 1990) because of applications in magnetic resonance imaging and ion cyclotron resonance. It illustrates the interplay between “pure science” and technology. Technology is pushed so hard in the pursuit of fundamental physics goals that practical applications with wider applicability can emerge.

C. TRAP I: ONE HUNDRED ANTIPROTONS COMPARED TO ONE HUNDRED PROTONS

In our first measurement (Gabrielse *et al.*, 1990), the cyclotron frequency of the center-of-mass of approximately 100 antiprotons was compared to that of protons. This measurement showed that the charge-to-mass ratios of the antiproton and proton are the same to within 4×10^{-8} , which is 40 ppb. The self-shielding solenoid kept the magnetic field drift from being a major factor at this accuracy. The improvement over earlier comparisons of antiprotons and protons using exotic atoms was more than a factor of 1000.

D. TRAP II: ALTERNATING ONE ANTIPROTON AND ONE PROTON

The second mass measurement compared a single trapped antiproton to a single trapped proton (Gabrielse *et al.*, 1995). The radio signal of single antiprotons was detected nondestructively (Fig. 19a). Owing to our high resolution, this measurement provided a spectacular illustration of special relativity (Fig. 19b,c) at eV energies insofar as the antiproton's cyclotron frequency

$$\omega_c = \frac{qB}{\gamma m} \quad (3)$$

depends upon the familiar relativistic factor $\gamma = (1 - v^2/c^2)^{-1/2} = E/mc^2$.

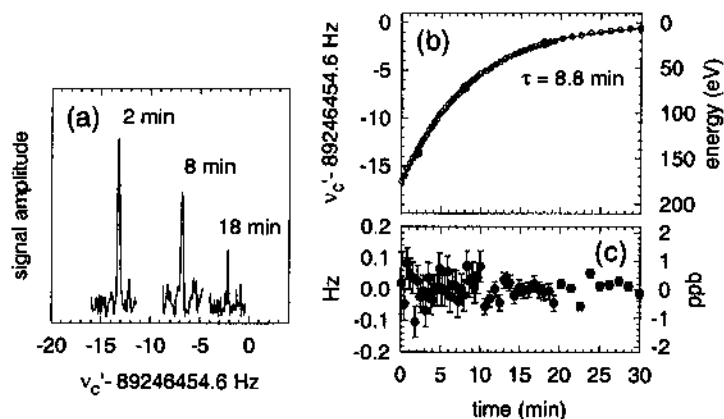


FIG. 19. Special relativity shifts the cyclotron frequency of a single trapped \bar{p} as its cyclotron energy is slowly and exponentially dissipated in the detector. Cyclotron signals for three subsequent times in (a) have frequencies highlighted in the measured frequency versus time points in (b). A fit to the expected exponential has small residuals (c) and gives the cyclotron frequency for the limit of no cyclotron excitation. (Taken from Gabrielse *et al.*, 1995.)

This second measurement showed that the charge-to-mass ratios of the antiproton and proton differed by less than 1×10^{-9} . The 1 ppb uncertainty arose almost entirely because the antiproton and proton have opposite sign of charge, and thus require externally applied trapping potentials of opposite sign. After the cyclotron frequency of one species was measured it would be ejected from the trap, the trapping potential would be reversed, and the second species loaded for measurement. Reversing the applied potential does not completely reverse the potential experienced by a trapped particle (e.g., due to the path effect on the inner surfaces of the trap electrodes). During the measurements of their respective cyclotron frequencies, the antiproton and proton thus reside at slightly different locations, separated by up to 45 μm in this case. If the nearly homogeneous magnetic field differs slightly between the broad locations, the measured v_c for the different species differs even if the charge-to-mass ratios do not.

E. TRAP III: SIMULTANEOUSLY TRAPPED ANTIPROTON AND H^- ION

The third and final measurement utilized a single antiproton and a single H^- ion trapped at the same time (Gabrielse *et al.*, 1999b). Both had the same sign of charge and were confined simultaneously, eliminating the systematic effect that limited the previous measurement. To keep the two from interfering with each other, one particle was always “parked” in a large cyclotron orbit. Measurements were made of the cyclotron frequency of the other particle in a small orbit at the center of the large orbit. The electron-to-proton mass ratio, the hydrogen binding energy, and the H^- electron affinity were well enough known that no additional error was contributed by substituting an H^- ion for a proton.

In the initial proposal to CERN I suggested that the most accurate q/m comparisons would come by comparing an antiproton and an H^- ion. During the TRAP I and TRAP II measurements we speculated occasionally about whether H^- ions might be formed during antiproton loading, but never got around to looking until we encountered the unavoidable disruption of an H^- ion loaded with a single antiproton. When we did look we found that we could always load negative ions with antiprotons. By reducing the number of cooling electrons we were able to typically load of order 500 H^- at the same time as antiprotons, presumably as hydrogen atoms liberated from the degrader picked up cooling electrons. The electrons then had to be ejected quickly to avoid collisional stripping of the H^- . Loading a single antiproton and H^- , and preparing them for measurement, typically required 8 h.

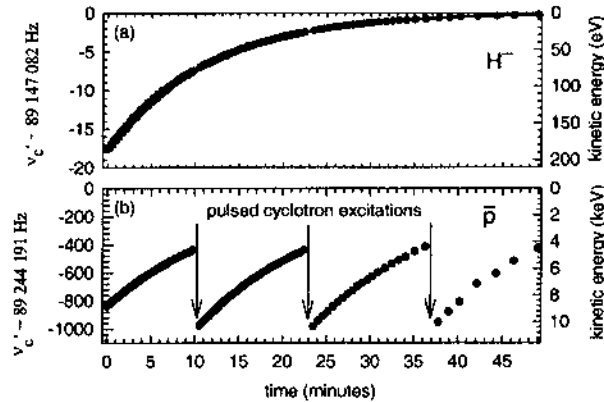


FIG. 20. (a) Special relativity shifts the cyclotron frequency of an H^- as our detector slowly removes its energy. (b) Similar signals from a \bar{p} kept simultaneously in a large orbit by three pulsed excitations. (Taken from Gabrielse *et al.*, 1999.)

This mass measurement established that

$$\frac{q}{m}(\bar{p}) \Big/ \frac{q}{m}(p) = -0.999\,999\,999\,91(9) \quad (4)$$

The accuracy exceeds that of the second TRAP measurement by more than a factor of 10 (Fig. 14b), and improves upon the earlier exotic atom measurements by a factor of 6×10^5 . At a fractional accuracy $f = 9 \times 10^{-11} = 90$ ppt there is thus no evidence for PCT violation in this baryon

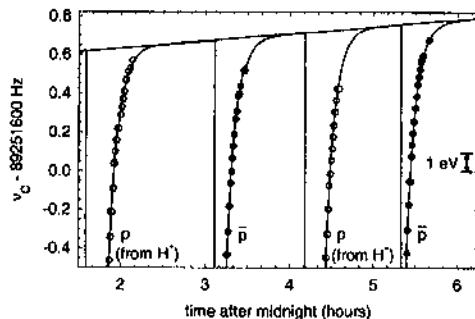


FIG. 21. Alternating cyclotron decays of p and \bar{p} (from H^-) superimposed upon a slightly drifting magnetic field. (Taken from Gabrielse *et al.*, 1999.)

system. This is the most precise test of PCT invariance with a baryon system by many orders of magnitude as is illustrated in Fig. 15.

The comparison of \bar{p} and H^- also uniquely establishes the limit $r_{\omega_c}^{H^-} < 4 \times 10^{-26}$, where $r_{\omega_c}^{H^-} = \hbar\omega_c(\bar{p})f/(mc^2)$ quantifies extensions to the standard model that violate Lorentz invariance, but not PCT (Bluhm *et al.*, 1998). Such violations would make $\nu_c(\bar{p})$ and $\nu_c(H^-)$ differ in addition to the familiar mass and binding energy corrections, without making $|q/m|$ different for \bar{p} and p .

Our apparatus was clearly capable of a higher accuracy, perhaps even another factor of 10, but LEAR closed down before these measurements could be pushed to their limit.

III. Opening the Way to Cold Antihydrogen

A. COLD ANTIHYDROGEN

Antihydrogen is the simplest of antimatter atoms, being formed by a positron in orbit around an antiproton. The pursuit of cold antihydrogen began some time ago, long before a few antihydrogen atoms traveling at nearly the speed of light (Baur *et al.*, 1996) generated great publicity. Unlike the extremely energetic antihydrogen, cold antihydrogen that can be confined in a magnetic trap for highly accurate laser spectroscopy offers the possibility of comparisons of antihydrogen and hydrogen at an important level of accuracy (Fig. 22). Gravitational measurements can also be contemplated (Gabrielse, 1988) because the antimatter atom is electrically neutral

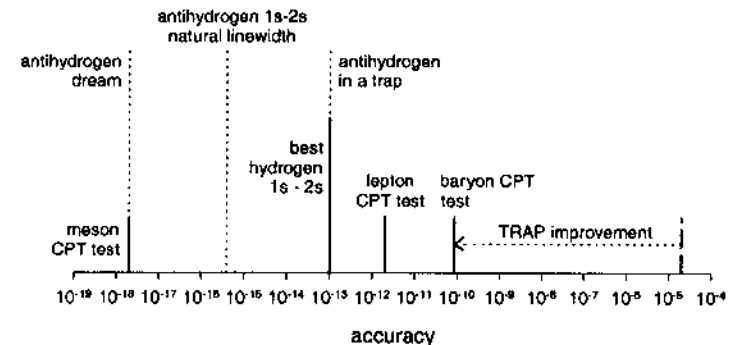


FIG. 22. Relevant accuracies for the precise 1s–2s spectroscopy of antihydrogen are compared to the most stringent tests of PCT invariance carried out with the three types of particles — mesons, leptons, and baryons.

and hence not very sensitive to electric and magnetic forces.

In my 1986 Erice lecture (Gabrielse, 1987), shortly after we had trapped antiprotons for the first time (Gabrielse *et al.*, 1986), I discussed the possibility of forming cold antihydrogen from cold, trapped antiprotons and positrons. I concluded:

For me, the most attractive way . . . would be to capture the antihydrogen in a neutral particle trap. . . . The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time.

I was inspired by the attempts to confine neutrons and the first trapping of atoms (Migdall *et al.*, 1985). During the time that we were developing the techniques to make cold antiprotons and positrons available for the production of cold antihydrogen, the trapping of atoms including hydrogen (Cesar *et al.*, 1996) also was becoming common.

The formation of cold antihydrogen requires first that its ingredients, cold antiprotons and cold positrons, be available in the extremely high vacuum that is desirable for accumulating these particles and for storing cold antihydrogen. The first half of this chapter focused upon the techniques required to slow, trap, cool, and accumulate 4.2 K antiprotons. In the following section we summarize the availability of 4.2 K positrons. The next step on the path to cold antihydrogen is to bring the cold ingredients together. The “nested Penning trap” (Section III.C), proposed for this purpose, has since been demonstrated. Section III.D summarizes an experiment in which we stored cold antiproton and positrons for the first time in either a nested trap or at 4.2 K—the closest approach yet to cold antihydrogen. Several different recombination mechanisms (Section III.E) will be investigated whereby cold antiprotons and cold positrons could recombine to form cold antihydrogen.

B. 4.2 K POSITRONS IN EXTREMELY GOOD VACUUM

Cold positrons are the other required ingredient for cold antihydrogen. Since only a few cold positrons had ever been confined in the extremely high vacuum that is desirable for cold antihydrogen experiments we set about capturing large numbers of cold positrons in this environment. We first used electronic damping (Haarsma *et al.*, 1995). Then we discovered and developed a new technique in which we produced Rydberg positronium and ionized it within a trap. This approach yielded a vastly improved accumulation rate (Estrada *et al.*, 2000), up to 10^5 positrons per hour for a 2.5 mCi ^{22}Na source.

Figure 23a shows the simplicity of the apparatus. A thin transmission moderator, a 2- μm tungsten crystal W(110), is added to an open access

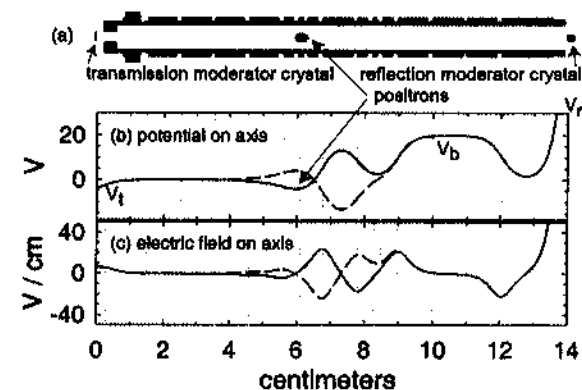


FIG. 23. The electrodes of an open access Penning trap (a) are biased to produce an electric potential (b) and field (c) along the central axis that confines e^+ (solid curves) or e^- (dashed curves). A 5.3 T magnetic field parallel to this symmetry axis guides fast positrons entering from the left through the thin crystal and towards the thick crystal. (Taken from Estrada *et al.*, 2000.)

Penning trap (Gabrielse *et al.*, 1989c) at one end. A thick reflection moderator, a 2-mm tungsten crystal W(100), is added at the other. Positrons from the radioactive source, traveling along field lines of a strong magnetic field (5.3 T), pass through the transmission moderator to enter the trap from the left. The electric field of the trap ionizes the Rydberg positronium, which then accumulates in the location shown.

Figure 24 shows the accumulation of more than a million positrons. We expect soon to increase the accumulation rate dramatically by simply increasing the size of the 2.5 mCi source to 150 mCi. The crucial time period for positron accumulation at the AD is of order of an hour, the amount of time it will take to stack a reasonable number of antiprotons in a trap.

C. DEMONSTRATING THE NESTED PENNING TRAP

The production of cold antihydrogen requires that antiprotons and positrons be allowed to interact. The nested Penning trap (Fig. 25) proposed for this purpose (Gabrielse *et al.*, 1988) was demonstrated experimentally (Hall and Gabrielse, 1996) with protons and electrons. The demonstration shows that a nested Penning trap should allow antiprotons and positrons to interact with a low relative velocity, as illustrated in Fig. 26. Without cooling electrons in the central well, hotter antiprotons retain the higher energy distributions, illustrated on the right-hand side of the figure. With cooling electrons in the well the antiproton energy spectrum cools dramatically as shown on the left-hand side of the figure.

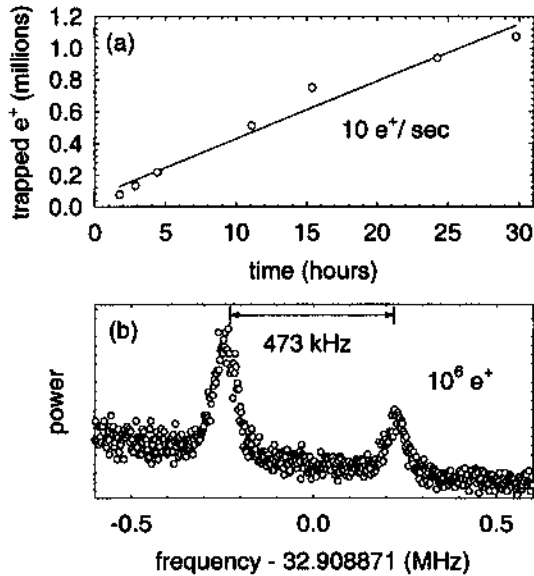


FIG. 24. (a) Accumulation of 1.1 million positrons and (b) their electrical signal. (Taken from Estrada *et al.*, 2000.)

D. CLOSER TO COLD ANTIHYDROGEN THAN EVER BEFORE

In the last week of LEAR's operation we got closer to cold antihydrogen than anyone has ever been before (Gabrielse *et al.*, 1999a). Figure 27 shows the first simultaneous confinement of 4 K antiprotons and positrons, and Fig. 28 shows trapped positrons heated by trapped antiprotons.

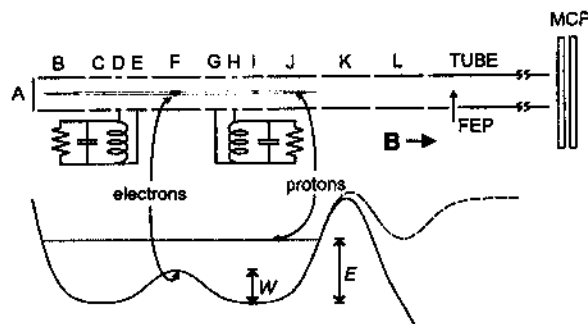


FIG. 25. Scale outline of the inner surface of the electrodes (a), and the potential wells (b), for the nested Penning trap. (Taken from Hall and Gabrielse, 1996.)

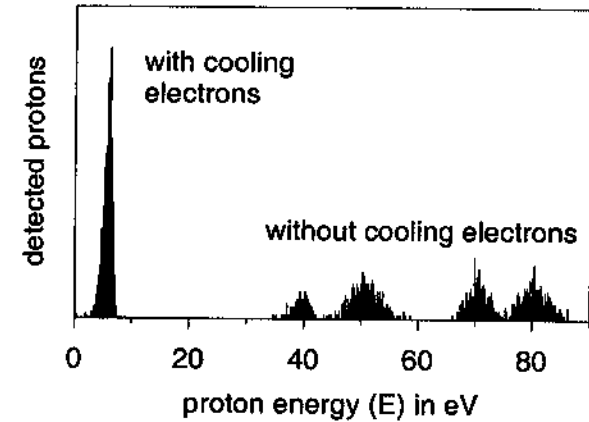


FIG. 26. Energy spectrum of the hot protons (right-hand side) and the cooled protons (left-hand side), obtained by ramping the potential on electrode K downward and counting the protons that spill out to the channel plate. The hot and cooled spectra for 4 initial proton energies are summed. (Taken from Hall and Gabrielse, 1996.)

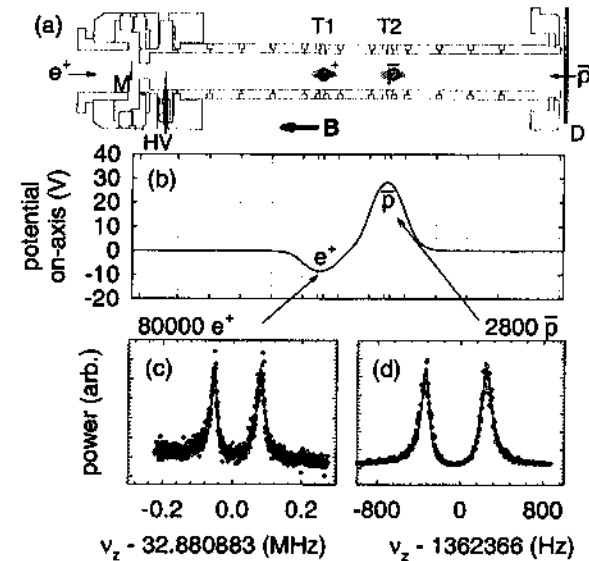


FIG. 27. (a) Electrode cross sections and the initial position of the simultaneously trapped \bar{p} and e^+ . (b) Trap potential on the symmetry axis. Fits (solid curves) to the electrical signals from simultaneously trapped e^+ (c) and \bar{p} (d) establish the number of trapped particles. (Taken from Gabrielse *et al.*, 1999a.)

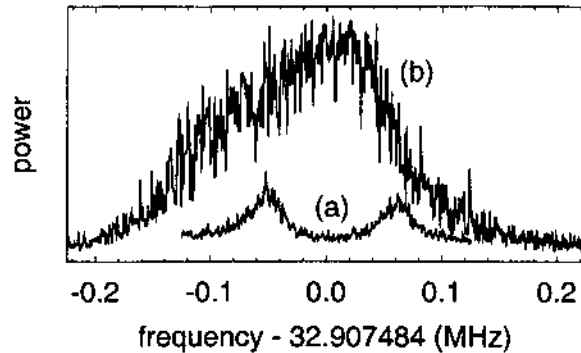


FIG. 28. The signal from cold trapped positrons (below) changes dramatically (above) when heated antiprotons pass through cold positrons in a nested Penning trap, showing the interaction of antiprotons and positrons. (Taken from Gabrielse *et al.*, 1999a.)

E. RECOMBINATION MECHANISMS

To form antihydrogen, a positron and antiproton must have kinetic energy to approach each other, and this energy must be removed to form an atomic bound state. Energy and momentum cannot be conserved unless a third particle is involved. Different antihydrogen formation processes provide different ways to conserve energy and momentum. Of course, this recombination must occur within the extremely good vacuum demonstrated with antiprotons or else the antihydrogen will not live long enough to be studied to an interesting accuracy. Long ago we compared different mechanisms by which cold antihydrogen might be formed in a Penning trap (Gabrielse *et al.*, 1988), suggesting that a “nested Penning trap” might provide the most useful environment.

Three of the antihydrogen formation processes that have been studied (and possibly one hybrid) are attractive candidates. A very nice feature of the nested Penning trap we have demonstrated is that it gives a very easy way to select one process from another, and to rapidly switch between them within the same apparatus. A shallow central trap will select a three-body recombination process. A deep central trap will select radiative recombination, whose rate can be enhanced by switching on an appropriate laser.

We will first consider the processes that look most attractive (Section III.E.1), then briefly look at other processes (Section III.E.2).

1. Selecting Processes Within a Nested Penning Trap

Within a shallow nested Penning trap, the electric field is very low. Antihydrogen initially formed in a high Rydberg state will be less easily

ionized when the electric field is low. (The positron plasma will screen the electric field along the axis of the magnetic field, but not in the radial direction.) The dominant process should then be the three-body processes



because this promises to have a much higher rate than any other process (Gabrielse *et al.*, 1988). De-excitation to the ground state takes some time (Glinsky and O’Neill, 1991; Fedichev, 1997), but not nearly so long as was originally thought (Menshikov and Fedichev, 1995). In a shallow central well it should be possible to use 10^6 antiprotons at 4 K, submerged within an extended plasma of 4 K positrons at a density of $10^7/\text{cm}^3$. (This density is lower by 10 than what we have already achieved in a deeper well.) Under these conditions, except with no magnetic field, the calculated recombination rate is an astounding $10^9/\text{s}$ (Gabrielse *et al.*, 1988). A strong magnetic field (e.g., from the trap containing antiprotons and positrons) would reduce this high rate (Glinsky and O’Neill, 1991) by approximately a factor of 10, and an electric field (also part of the trap) also has some effect (Menshikov and Fedichev, 1995), but the rate is still higher than for any other recombination processes. The related three-body recombination process



has also been mentioned (Gabrielse *et al.*, 1988).

Within a deeper nested Penning trap, there will be a much stronger electric field in the central region where antiprotons and positrons interact. The rapid three-body mechanism (Eq. 5) should thus be essentially turned off since antihydrogen initially formed in a high Rydberg state will be ionized before de-excitation occurs. The slower radiative recombination process would then be selected, and it could be enhanced by the illumination of an appropriate laser.

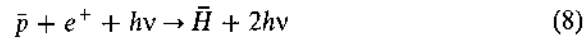
Radiative recombination can be thought of as producing an excited hydrogen atom that radiates a photon to conserve energy and momentum,



This process suffers from a lower rate because it takes approximately a nanosecond to radiate a photon, much longer than the duration of the interaction between a \bar{p} and an e^+ , even when these particles have an energy low enough to correspond to 4 K. For 10^6 antiprotons at 4 K within a 4 K positron plasma of density $n_e = 10^8/\text{cm}^3$ (a positron density that we have already realized), the estimated recombination rate (Gabrielse *et al.*, 1988)

is $3 \times 10^3/s$. The radiative recombination process has the attractive feature that most of the antihydrogen is formed in the ground state. If we succeed in increasing the positron density to $10^{10}/\text{cm}^3$, this rate would be 100 times higher.

The radiative recombination rate can be increased by stimulating the process with a laser,



Laser-stimulated, radiative recombination has been observed in merged beams (Schramm *et al.*, 1991; Yousif *et al.*, 1991) but has yet to be observed in a trap. It has the useful diagnostic feature that the formation rate will increase sharply as the laser is tuned through resonance. For cold positrons and antiprotons, the two transitions that are easily accessible with relatively high power lasers are to $n = 3$ at 820.6 nm, and to $n = 11$ at 11,032 nm (Gabrielse *et al.*, 1988).

Stimulating to $n = 11$ has the higher rate, and subsequent radiation will take 99% of the population to the ground state. A N_2O laser or a $^{13}\text{CO}_2$ laser with a modest and manageable power of 10 W/mm^2 will nearly saturate the transition. Nearly 2% of the antiproton should be converted to antihydrogen at this power for a positron density of $10^7/\text{cm}^3$. We use this low positron density because here a hybrid process could be even more attractive. The rate would be much higher if a three-body recombination to approximately 4 kT below the ionization limit was followed by a laser-stimulated recombination to $n = 11$.

2. Other Formation Processes

Another antihydrogen formation process has been extensively discussed. The process uses positronium, the bound state of an electron and a positron, with the electron carrying off the excess (Humbertson *et al.*, 1987).



One advantage is that the antihydrogen is produced preferentially in the lowest states. When antiprotons are not available, the charge-conjugate process can be studied (recombining protons and positronium to form hydrogen and positrons). This was recently observed (Merrison *et al.*, 1997) using a beam of protons. Unfortunately, comparable quantities of antiprotons are very difficult to arrange. It should be possible to increase the recombination rate by initially exciting the positronium atom with a laser

(Charlton, 1990). Nonetheless, the disadvantage of the recombination using positronium is that the projected rate is still extremely low for both realizable numbers of antiprotons and existing positronium beams. Estimates place the production rate at perhaps 100 atoms per day for continuous production at the AD, or perhaps 2 antihydrogen atoms per pulse of 10^{10} positrons if this could be arranged (Surko *et al.*, 1997). With such a low rate, and an apparatus somewhat different from what is required for the other formation processes, we do not plan to pursue this approach. However, we are intrigued by the possibility that the high Rydberg positronium we have already realized may allow us to resurrect it.

Finally, there are more recent suggestion. Charge exchange processes may provide a route to the formation of cold antihydrogen (Hessels *et al.*, 1997). Recombination of electrons and positive ions aided by an electric field, has recently been observed (Wesdorp *et al.*, 2000); this technique may be applicable to antihydrogen formation as well. We are investigating both routes.

F. FUTURE

A substantial Antiproton Decelerator (AD) facility is nearing completion at CERN to carry forward experiments with low energy antiproton. It looks like the AD will be delivering useful numbers of antiprotons in fall 2000, and meeting (or even exceeding) its design specifications in summer of 2001. Two large collaborations have formed to produce and study cold antihydrogen. Our TRAP collaboration expanded to become ATRAP (ATRAP, 2000). Our competition is ATHENA (ATHENA, 2000), which grew out of the attempt mentioned earlier to measure the gravitational acceleration of antiprotons. In July, our ATRAP collaboration announced the first trapping of antiprotons from the AD, the first electron-cooling of these trapped antiprotons, and began stacking antiprotons in a trap. ATHENA apparatus should be ready soon. Experiments to build upon the TRAP foundation have just begun.

Despite some claims to the contrary, antihydrogen production is a very difficult undertaking that will take some time. Estimated production rates are dauntingly low even though it should be possible to detect single antihydrogen atoms, by detecting the pions from antiproton annihilation and the gammas from positron annihilation. New techniques must be devised to cool antihydrogen to the low energies required for trapping, since current hydrogen cooling techniques involve collisions with cold surfaces that would cause the antihydrogen to be annihilated. It also remains to be demonstrated that useful spectroscopic measurements can be done with only a few antihydrogen atoms in a trap. The cause is worthy but many challenges remain.

IV. Technological Spinoffs

In the pursuit of fundamental measurements it is not uncommon to push technology very hard with the result that unpredicted new techniques and devices emerge. I mention two examples from our antiproton studies:

- The charge-to-mass measurements required a very stable magnetic field, but were performed in an accelerator hall where the cycle of the Proton Synchrotron (PS) caused the magnetic field in our experiment to make a large change every 2.4 s. Our solution was to invent a self-shielding superconducting solenoid (Gabrielse and Tan, 1988). We demonstrated (Gabrielse *et al.*, 1991) that this addition reduced the size of the fluctuations in the magnetic field by a factor of 150 or more. Without this invention the extremely accurate q/m measurements would not have been possible. The same invention makes it possible to do more accurate ion cyclotron resonance (ICR) measurements (to analyze the composition of potential drugs, etc.) and nuclear magnetic resonance. The self-shielding solenoid is now patented (Gabrielse and Tan, 1990) and available commercially.
- The open endcap Penning trap (Gabrielse *et al.*, 1989c) we developed to allow antiprotons to enter our trap will also provide ready access for any other charged particle, laser beams, etc. This design is increasingly being used as the cell design of choice for ICR measurements

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