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Extremely Cold Antiprotons

Cooling and trapping of these particles at energies one ten-billionth of what was feasible six years ago should make possible production of the first antimatter atoms

by Gerald Gabrielse

How does one store an antiproton? The antimatter counterpart of the familiar proton (a building block of ordinary matter, along with the electron and the neutron), the antiproton is believed to have the same amount of charge as the proton, but the charge is negative instead of positive. A single collision between a proton and an antiproton can annihilate both particles. In a burst of energy the antiproton and proton cease to be, and a variety of particles (most of which are called pions) are formed. As a consequence, antiprotons cannot be confined by the walls of an ordinary container, nor can they come into contact with the ordinary atoms making up the atmosphere. The only way to store an antiproton is in a nearly perfect vacuum, using magnetic and electric fields to make a container without walls.

The past few years have seen a remarkable blossoming in the ability to cool and store antiprotons. Storage techniques involving magnetic fields have been common since 1955, when the Bevatron storage ring at the University of California at Berkeley was constructed to confine antiprotons. Yet the antiprotons in such large rings are extremely "hot": they typically travel at speeds approaching the limiting speed of light and have extremely high energies, ranging from a billion to a trillion electron volts (1 GeV to 1 TeV). High speeds and energies are acceptable and even desirable for experiments in which antiprotons collide with other particles, but other interesting experiments require "cold" antiprotons that move slowly and have low energies. Such experiments are needed in order to test accurately our understanding of matter and antimatter, as well as theories that underlie the nature of both substances.

Recently a small international team, of which I am a member, demonstrated the ability to slow and cool antiprotons to energies one ten-billionth of what was possible just six years ago. The cold antiprotons can be stored for as long as desired, even for several months, in a nearly perfect vacuum that is less than a cubic millimeter in volume. The average energy of the antiprotons is so low—less than one thousandth of an electron volt—that it is typically expressed in terms of temperature units. (A fortieth of an electron volt corresponds to room temperature.) The antiprotons in our storage device have a temperature of only four degrees above absolute zero (four kelvins).

Extremely cold antiprotons are already being exploited to compare the charges and masses of antiprotons and protons at a level of accuracy more than 1,000 times greater than was previously possible. Such comparisons stringently test the so-called *PCT* theorem of particle physics, which predicts that the antiproton and proton should have identical masses and charges that differ only in sign. We expect a substantial improvement in accuracy over the next several years. Someday cold antiprotons might even be used to observe the first antimatter atoms. By combining an antiproton with a positron (an antielectron), it should be possible to produce antihydrogen.

Antiprotons occur naturally only as the rare products of collisions between high-energy cosmic rays and atoms in the atmosphere. Although they are believed to be stable—that is, they do not spontaneously decay into other particles—such naturally occurring antiprotons nonetheless live for only a very short time. Soon after they come into being, they annihilate in collisions with protons that are in the atmosphere.

Antiprotons are created artificially in particle accelerators by colliding extremely high energy protons with solid matter. CERN, the European laboratory for particle physics near Geneva, generated collisions between large numbers of antiprotons and protons to observe and study the short-lived *W* and *Z* particles. At the Fermi National Accelerator Laboratory in Batavia, Ill., higher-energy collisions between antiprotons and protons are now being investigated as a continuation of a long search for the top quark. This particle is the only member of a group of six constituents of heavy particles (such as protons) that has not been observed.

New experiments with antiprotons became possible when workers at CERN scavenged parts from earlier storage rings to complete the Low Energy Antiproton Ring (LEAR) in 1982. LEAR has a modest circumference of only 79 meters, which is tiny compared with the 85-kilometer circumference of the contemplated 20-TeV Superconducting

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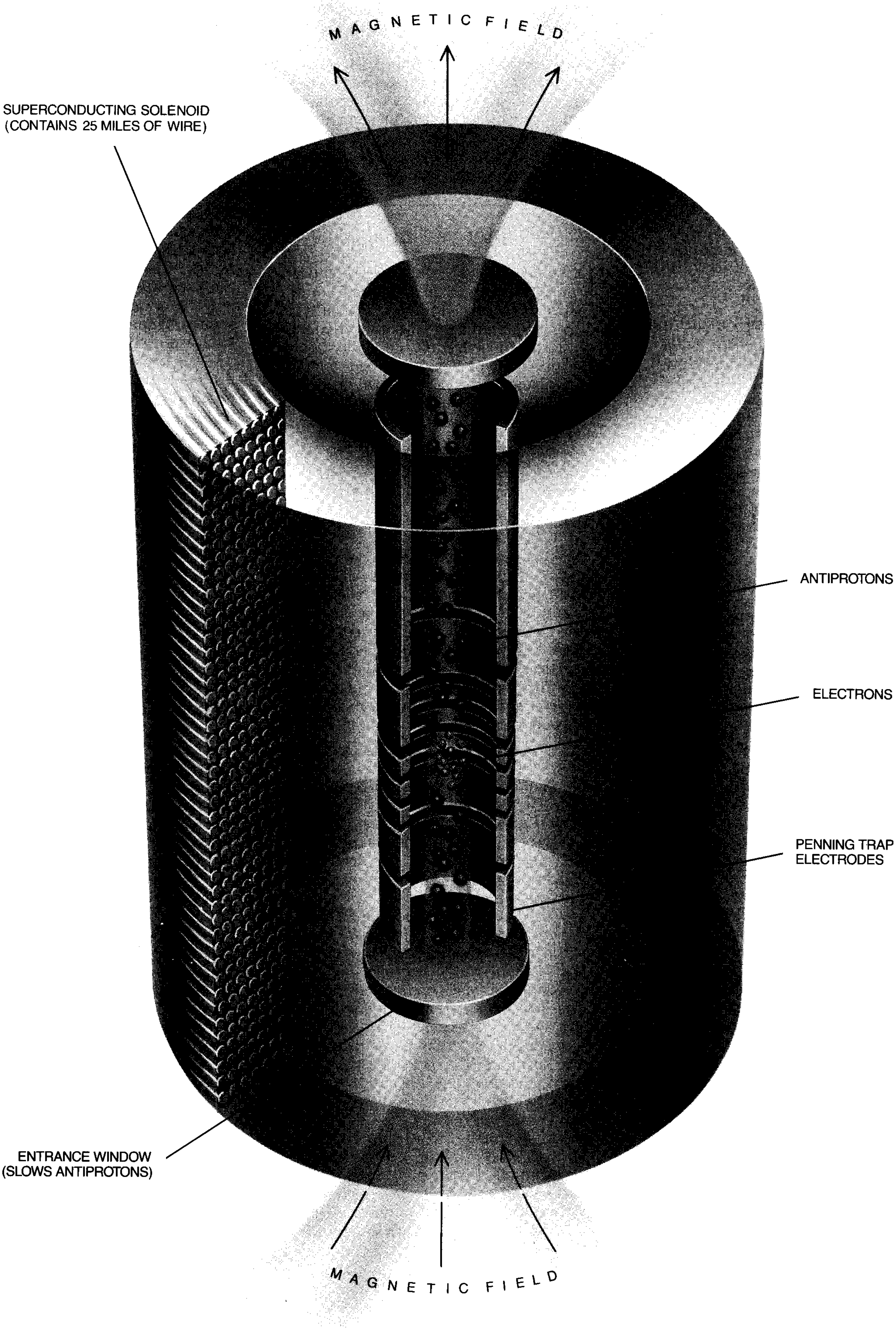
ION TRAP captures antiprotons (*red*), which are cooled by collisions with cold electrons (*green*). The antiprotons and electrons are held by electric and magnetic fields; the electric field is produced by applying voltages to electrodes, and the magnetic field is generated by a superconducting solenoid, or coil (not to scale).


MAGNETIC FIELD
SUPERCONDUCTING SOLENOID (CONTAINS 25 MILES OF WIRE)
ANTIPROTONS
ELECTRONS
PENNING TRAP ELECTRODES
ENTRANCE WINDOW (SLOWS ANTIPROTONS)
MAGNETIC FIELD

Super Collider. LEAR regularly slows and cools antiprotons to an energy of six million electron volts (MeV), which corresponds to a speed that is approximately 10 percent that of light.

Our apparatus is able to cool antiprotons to energies one ten-billionth of those obtained at LEAR, and it is so small that it falls in the realm of the "tabletop." A major complication is that the tabletop must be connected to a series of large particle physics accelerators, such as the machines at CERN, that are capable of supplying antiprotons having energies of a few MeV.

In 1981 I visited Fermilab to explore the possibility of trapping and storing extremely cold antiprotons. Fermilab was closer to home than was CERN, and it had a small storage ring in operation, which seemed adaptable to the project. Unfortunately, the intense focus on studying high-energy collisions between protons and antiprotons left little room for the low-energy experiments envisioned. Cooler heads did not prevail. By 1984, pieces of the small storage ring were being trucked to other laboratories. William Kells of Fermilab and I thus turned our attention to mounting an experiment in Geneva, since the LEAR facility had now become the only laboratory in the world that could slow antiprotons to the MeV-range energies our proposed tabletop apparatus could accept. Hartmut Kalinowsky of the University of Mainz joined forces with us, as did Thomas A. Trainor of the University of Washington.

Oversight committees and administrators at CERN greeted our proposals with some skepticism. We sought to slow the antiprotons in matter, capture them in an ion trap and cool them through collisions with cold electrons in the same trap. (An ion trap confines charged particles, or ions, by means of magnetic and electric fields.) These unproved techniques were quite different from the usual high-energy collision experiments. Moreover, one of our physics goals was in direct competition with a proposed experiment (a large radio-frequency mass spectrometer) in which CERN had already invested a great deal of time and money. There was also much concern because we had no financial support. At the same time, agencies in the U.S. were cautious about funding a large new program to be done at CERN, one that did not yet have approval there. Fortunately, the Atomic Physics Division of the National Science Foundation, followed by the Air Force Office of Scientific Research and the National Bureau of Standards, decided to fund the request for low-energy antiprotons. Somewhat later the German State Ministry for Research joined in.

In May 1986, CERN granted us 24 hours of access to LEAR antiprotons to demonstrate that it actually was possible to slow them from several million to a few thousand electron volts. Our demonstration worked, and we were rewarded by a second 24-hour access period two months later, in which we sought to show that we could capture the slowed antiprotons.

Energy Units

The electron volt (eV) is the energy acquired by an electron when it travels from the negative to the positive terminal of a one-volt battery. An eV is the typical unit of energy used to describe electrons bound in atoms. Standard metric prefixes are added to represent the larger and smaller energies needed to describe the experiments that are discussed in this article:

1 TeV = 1,000,000,000,000 eV = 10^{12} eV
1 GeV = 1,000,000,000 eV = 10^{9} eV
1 MeV = 1,000,000 eV = 10^{6} eV
1 keV = 1,000 eV = 10^{3} eV
1 meV = 0.001 eV = 10^{-3} eV

Small energies are sometimes represented in temperature units, in degrees above absolute zero (K), with 1 meV $\sim$ 12 K. The much larger GeV and TeV, used to describe the energy of accelerated particles, are still very small compared with the kinetic energy ($E = \frac{1}{2} Mv^2$) of macroscopic objects of mass M and speed v. For example, a one-gram paper clip dropped one meter strikes the ground with a kinetic energy on the order of 10^{17} eV = 10^{5} TeV.

Unfortunately, we had insufficient time to obtain modern equipment with which to build an ion trap. Borrowing an ancient superconducting magnet, we constructed a trap in one day, relying on glass-to-copper seals of unknown origin that we found abandoned in a glassblower's drawer. Our trap was chilled to a temperature of four kelvins by thermal contact with liquid helium within a dewar, a vacuum-insulated vessel similar to a thermos bottle. After testing the apparatus in the U.S., we shipped it by air to CERN because of the pressure of time and the delicate nature of the dewar we had built. Only after the dewar arrived broken in Geneva did we learn that our "air" shipment had in fact rattled across Europe by truck.

Repairing the abused dewar turned out to be an exercise in improvisation. It is hard to forget aiming a sputtering hand torch at "borrowed" high-temperature solder placed on thin tubes, within an apparatus that dangled from a rope tied to an exposed beam in a CERN hallway. The repaired apparatus was ready several days before the antiprotons were scheduled to arrive, which was at noon on Friday, July 17. Feverish computer programming proceeded, punctuated by calls of "just one half-hour more of BASIC" as we sought to interface our computer with devices at LEAR in order to read out information about attempted antiproton captures as they happened.

Then, late Thursday evening, disaster struck. Routine tests unexpectedly revealed that we could no longer apply high voltages to our ion trap without causing an unwanted electric arc deep inside the coldest part of the apparatus. It was 12 hours before the antiprotons were scheduled to arrive, and this apparatus had never been warmed to room temperature and then cooled back to four kelvins in less than several days. Half of our team gave up and went to bed.

Given CERN's ambivalence about the feasibility of the proposed experiments, a failure would clearly be a major setback. A repair had to be attempted. As we opened the cold apparatus, water that had condensed on the "super"-insulation streamed out, despite the hot air directed on it from three industrial-strength hair dryers. Eventually we eliminated the arc by installing fresh cables to handle the high voltages. After much mopping of water, drying and cleaning, we reassembled the apparatus and began cooling it by 10 A.M. Friday.

We told the LEAR control room that shortly after noon we would indeed be ready for our antiproton test. Our exhausted euphoria was short-lived. We were told by telephone that although antiprotons were available in one of the large storage rings at CERN, the "kicker" used to extract antiprotons from the ring had failed. We would most likely have to leave CERN without receiving antiprotons. The test experiment seemed doomed, since LEAR was shortly scheduled to be shut down for more than a year. I made known the urgency of our situation, then stumbled off to bed.

Several hours later I was awakened. A particle accelerator "magician" at

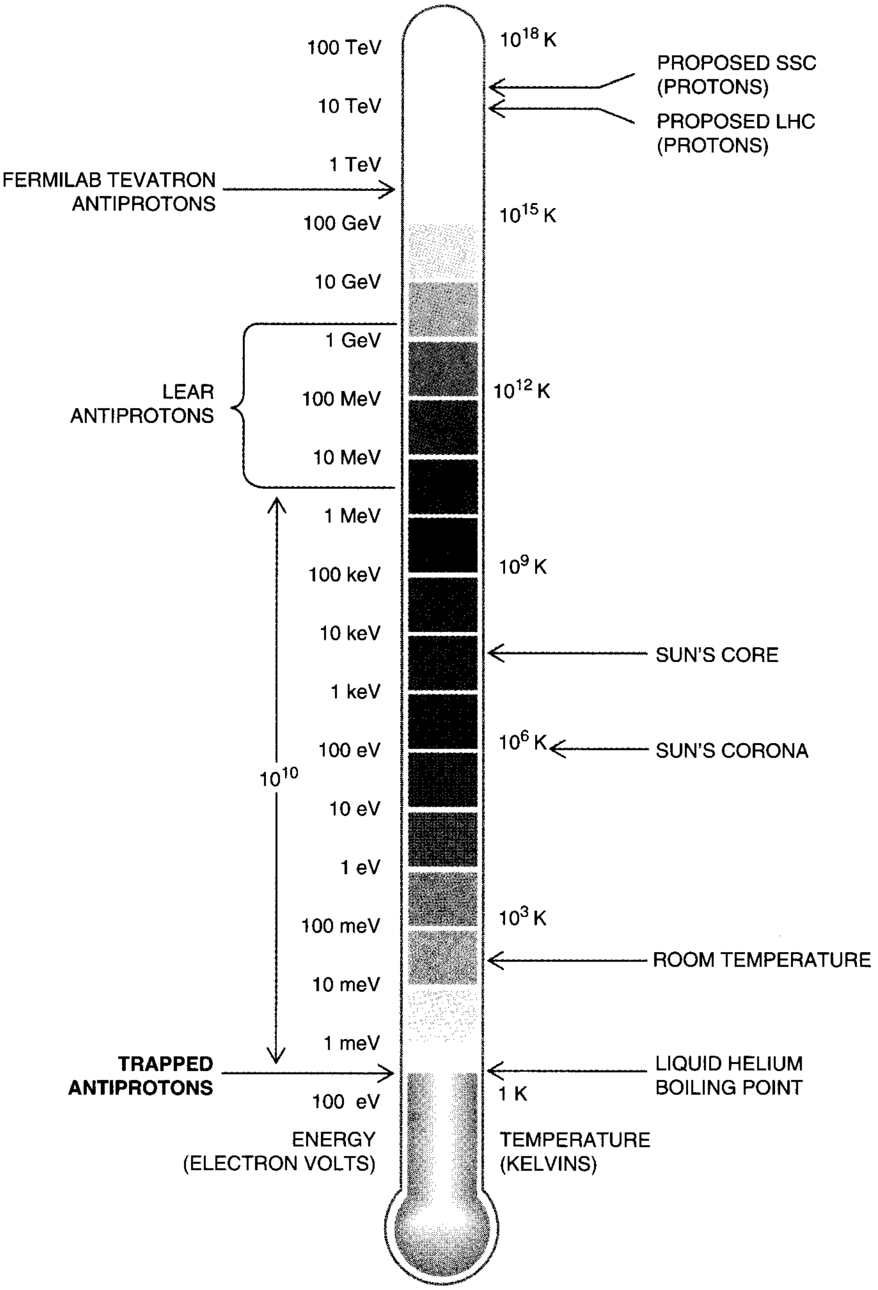
CERN had managed to make a backup "kicker" work for the first time. Soon LEAR was ready to send us brief, intense pulses, or bursts, of antiprotons. (Typically each pulse contained 100 million antiprotons and had a duration of 200 billionths of a second.) Operators counted "five, four, three, two, one" 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 observed pions from the annihilation of antiprotons that we had trapped briefly and then released.

The emotional rollercoaster ended on a pronounced high. LEAR operators and physicists from other experiments crowded around the console during the countdown. Applause broke out whenever the histogram on the computer monitor indicated that antiprotons had been trapped and stored. A few antiprotons were held for 20 minutes, establishing the feasibility of the proposed experiments.

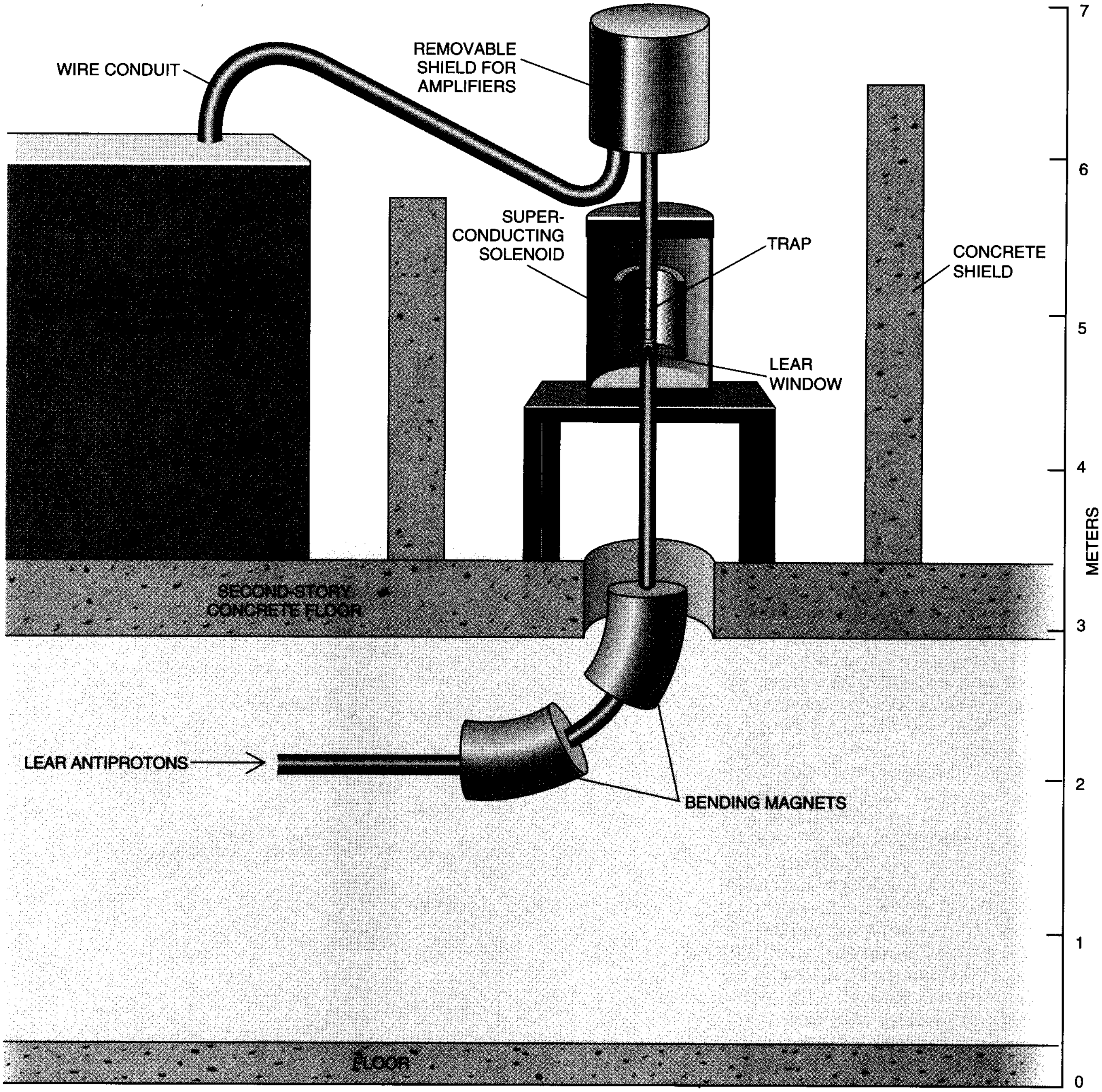
CERN enthusiasm now replaced CERN ambivalence. A semipermanent connection to LEAR was constructed for our experiments when the machine was shut down for one year. Our present apparatus, which we installed in 1988, now sits on a platform 4.3 meters above the ground. At the heart of the antiproton cooler lies the ion trap, a stack of gold-plated copper rings located in a magnetic field [*see illustration on page 79*]. Within the trap, charged particles make circular orbits perpendicular to the direction of a six-tesla magnetic field. The field, which is approximately 10 times more powerful than that generated by a strong permanent magnet, is produced by sending 37 amperes of current through a 25-mile coil of superconducting wire. Once the current has been introduced in the coil, it flows with no resistance, in seemingly perpetual motion. No external power is needed. Additional correction coils make the magnetic field constant over the small volume that is to be occupied by the antiprotons.

Voltages applied to electrodes in the trap keep charged particles from escaping out the upper and lower ends of the device. Electrons are trapped in a small, cloudlike formation before any antiprotons enter the trap. Negative tens of volts applied to the ring electrodes on either side of the small trapping region repel the electrons toward the center of the trap, where they are confined. The electrons rapidly radiate their energy, typically in a tenth of a second, and cool to the four-kelvin temperature of the surrounding electrodes. The trap is now prepared for the antiprotons.

The antiprotons crash through the bottom electrode of the trap, arriving in an intense 6-MeV pulse from LEAR. Immediately they begin to lose energy in random collisions with the particles that make up the electrode. Some antiprotons slow to a stop within the electrode and eventually annihilate. Others emerge along the axis of the trap with an energy that exceeds 3,000 electron volts (3 keV). These strike the upper electrode and annihilate. The remaining antiprotons, whose energies are below 3 keV, are those we can trap. Their number is maximized, typically to one in 5,000 of the incident antiprotons, by carefully choosing the thickness of the electrode. The filtered antiprotons travel upward until, repelled by the negative



ENERGY THERMOMETER contrasts the extremely large range of energies at which antiprotons (and protons) are stored for study. Each demarcation is a factor of 10 lower in energy than the one above. The Large Hadron Collider (LHC), proposed for CERN, the European laboratory for particle physics, and the Superconducting Super Collider (SSC), proposed for Texas (both to use protons), are at the top, and the Low Energy Antiproton Ring (LEAR) at CERN is in the middle. The new low-energy frontier described in the article is at the bottom, one ten-billionth of the LEAR energies. The energy units are electron volts [*see box on page 80*], and the corresponding temperatures are expressed in kelvins (K).



ANTIPROTON JOURNEY into the trap apparatus begins at the lower left of the illustration, and the particles are turned upward by two bending magnets. The antiprotons leave the LEAR vacuum and enter the vacuum of the antiproton trap through a pair of windows located within the cold apparatus, which sits on a "tabletop" 4.3 meters above the ground.

voltage of the upper electrode, they turn around and head back. To prevent their escape, the "entrance window" (bottom electrode) is "slammed shut" by applying a -3,000-volt potential to it in less than 20 billionths of a second.

The captured antiprotons oscillate back and forth along the 12-centimeter length of the trap, passing through the cold, trapped electrons. Just as a heavy bowling ball would ultimately be slowed by collisions with light Ping-Pong balls, virtually all the antiprotons cool to thermal equilibrium with the trapped electrons in less than two minutes. (Electrons are the ideal cooling agent insofar as they cannot annihilate the precious antiprotons.) Typically 10,000 antiprotons from a single LEAR pulse are cooled in the small trap. Once the antiprotons are cooled, the electrons are allowed to leak out by selectively heating them with radio waves, as we temporarily reduce the confining voltages on the trap electrodes. We have observed no loss of extremely cold antiprotons, even when the particles were held for two months.

An immediate consequence of the long-term storage is that we have shown the antiproton to be stable for at least 3.4 months. Although notably less than the 10^{25}-year proton lifetime limit, our figure stands as the longest direct determination of the antiproton's lifetime. It could be made because there are fewer than 100 background gas atoms per cubic centimeter in the trap. This is a remarkably low pressure limit

(5×10^{-17} torr), a millionth of what can be measured by commercial vacuum gauges. Our high vacuum is achieved because background gas atoms stick to the cold electrodes within a tightly sealed container.

Once we had successfully stored the extremely cold antiprotons, we were able to measure and compare the mass of that particle with the mass of the proton 1,000 times more accurately than had previously been possible. Our effort was aided by Xiang Fei, Luis A. Orozco, Steve L. Rolston and Robert L. Tjoelker, from my research group at Harvard University, and by Johannes Haas of the University of Mainz.

The measurements are based on the fact that the "cyclotron" frequency of the circular orbit of a charged particle in a magnetic field is simply the product of the charge of the particle and the strength of the magnetic field, divided by the mass of the particle. In other words, a massive particle orbits more slowly than a light particle does. In the strong magnetic field we use, antiprotons and protons make approximately 90 million revolutions per second. We detect the radio signal emitted by the rapidly orbiting particles and measure the cyclotron frequency, which is 90 million cycles per second (90 MHz), by means of an FM radio receiver. We found that the antiproton and proton orbital frequencies were the same to within four parts in 100 million.

Much of the experimental effort goes into evaluating and reducing the uncertainties, taking into account the effects of the somewhat more complicated orbital motion actually exhibited by the particles in the trap. Because we made sure that the magnetic field did not change between the measurements, the charge-to-mass ratio of the antiproton and proton is shown to be the same to within four parts in 100 million. If both particles are assumed to have the same amount of charge, the mass of the antiproton is the same as the mass of the proton to within the same limit.

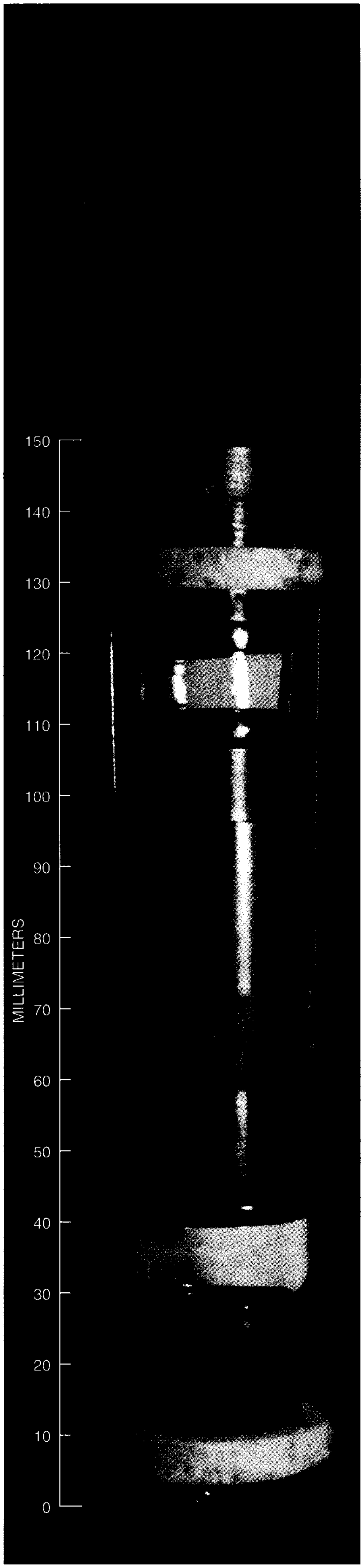
Holding the magnetic field constant during the measurements is especially difficult because the magnets in the nearby particle accelerator are turned on and off every 2.4 seconds. Fortunately, my graduate student Joseph N. Tan and I discovered we could design a superconducting solenoid, or wire coil, that senses changes in the external magnetic field and adjusts its own magnetic field to cancel those changes. The solenoid, which also supplies the strong magnetic field needed for our measurements, reduces fluctuations by a factor of 156. Our invention, now patented because of likely applications for magnetic resonance imaging and ion cyclotron resonance mass spectroscopy, illustrates the interplay between pure science and technology. The pursuit of fundamental physics goals pushes technology so hard that practical applications emerge.

In the near future we hope to measure the orbital frequencies of the antiproton and proton even more accurately. Several collaborators have now replaced graduate students and postdoctoral fellows who have moved on: Wonho Jhe, David Phillips and Wolfgang Quint, from my group at Harvard, and Julian Gröbner of the University of Mainz. Our early work has been promising—we have already increased the precision of our measurement by an additional factor of 40. We are also looking into the possibility of measuring the magnetic moment of the antiproton. The particle acts like an extremely small bar magnet; the magnetic moment is the effective strength of this magnet.

More accurate comparisons of antiprotons and protons will be difficult in the environment of a particle accelerator, and so it may become necessary to move antiprotons in our tabletop apparatus to a nearby location. In a similar apparatus, Harvard graduate student Ching-Hua Tseng and I recently transported trapped particles more than 3,000 miles across the U.S., from California to Nebraska and then from Nebraska to Massachusetts.

Comparisons of the orbital cyclotron frequencies of antiprotons and protons test the *PCT* invariance theorem. Historically, *P*, which stands for parity, was examined first. To understand the concept, imagine conducting an experiment in which the outcome is watched in a mirror. Now suppose a second experiment is constructed that is the mirror image of the first. If parity is conserved, the outcome of the second experiment should be identical to the outcome observed as the mirror image of the first experiment performed.

Until 1956, it was believed that reality was invariant under such a parity transformation. Early that year, however, Tsung-Dao Lee and Chen Ning Yang, then at Columbia University and the Institute for Advanced Study in Princeton, N.J., respectively, realized that the invariance of parity in weak interactions,



FIRST ANTIPROTON TRAP consisted of simple copper electrodes that were separated by glass spacers.

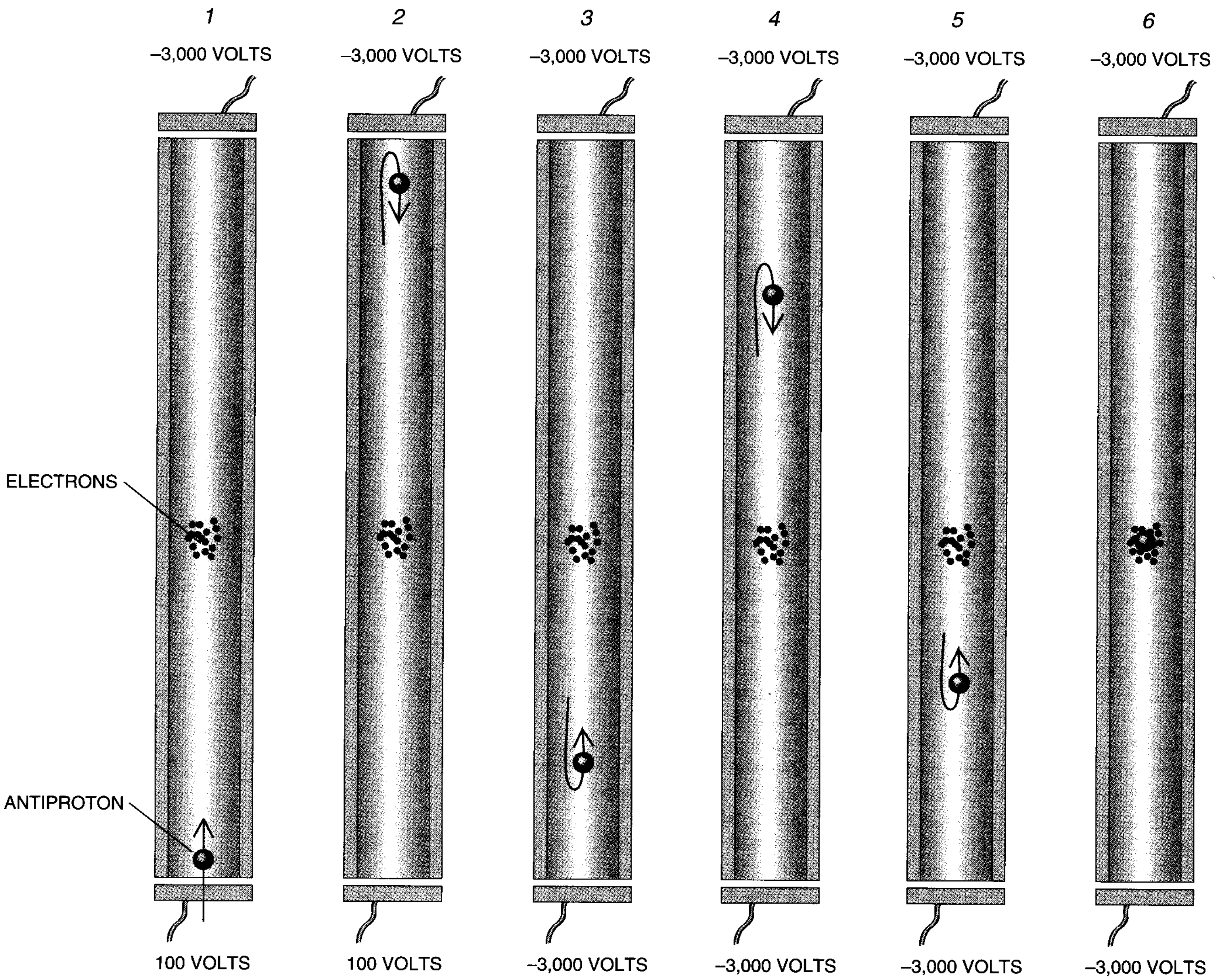
which are responsible for radioactive decay, had not yet been tested. Later that year Chien Shiung Wu and her colleagues at Columbia showed that mirror-image experiments did not produce mirror-image results when weak interactions were involved. The widespread belief in parity conservation was shattered.

Faith in a new invariance, *PC,* rapidly replaced the discredited notion. *C* stands for charge conjugation, a "thought experiment" process that turns particles into their corresponding antiparticles. To test whether *PC* is conserved, a mirror-image experiment is constructed, and all the particles in the experiment are replaced with their corresponding antiparticles. In 1964 James Cronin and Val L. Fitch, then at Princeton University, used particles called kaons to demonstrate, explicitly and unexpectedly, that *PC* is not conserved [see "A Flaw in a Universal Mirror," by Robert K. Adair; SCIENTIFIC AMERICAN, February 1988].

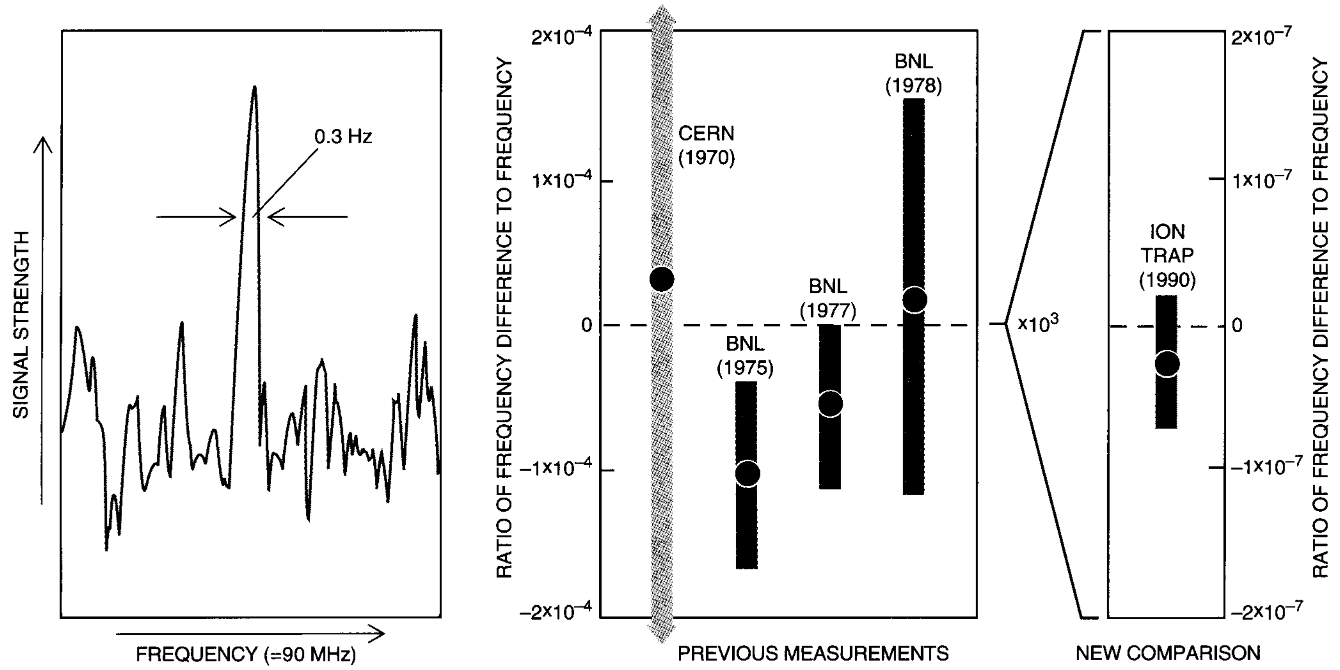
Today most physicists believe that *PCT* is invariant (the *T* stands for time reversal). Thus far theorists have yet to construct a reasonable theory in which *PCT* is not conserved. To test the invariance of *PCT,* imagine making a movie of an experiment's mirror image in which all the particles have been replaced by their corresponding antiparticles. Then a second experiment is performed to mimic what one sees in the film when it is run backward—when "time is reversed."

A consequence of *PCT* invariance is that the circular cyclotron frequencies of the antiproton and proton in a magnetic field should be identical. Our comparison thus tests *PCT* invariance and establishes that violations are smaller than the experimental uncertainties. Our experiment is currently one of the most accurate tests of *PCT* invariance. As our accuracy increases, we shall see whether this invariance of *PCT* continues to hold.

In the more distant future, extremely cold antiprotons should make it possible to produce and study antihydrogen, the antimatter atom formed by a positron in orbit around an antiproton. (Positrons, or antielectrons, are produced naturally in the radioactive decay of atomic nuclei.) Under the proper conditions, small numbers of



ANTIPROTON CAPTURE begins as the particle (*red*) leaves the entrance-window electrode within which it was slowed (*1*) and travels upward until it is repelled by –3,000 volts on the upper electrode (*2*). Reversing its direction, the antiproton travels downward toward the entrance window, until it is repelled there because the voltage on this window has in the meantime been changed from +100 to –3,000 volts (*3*). (The entrance window is initially held at +100 volts to prevent large numbers of electrons liberated from the electrode during the passage of antiprotons through it from entering the trap.) The antiproton is thus trapped, oscillating up and down between the two repulsive voltages. Repeated collisions (*4, 5*) with the electrons (*green*) in the trap cool the antiproton until it resides within the electron cloud (*6*).



ANTIPROTON RADIO SIGNAL (*left*) from the circular cyclotron motion of trapped antiprotons is strongest at the cyclotron orbit frequency. The ability to measure the difference between the circular frequencies of protons and antiprotons in a strong magnetic field is improved by a factor of 1,000 by using extremely cold antiprotons (*right*). Earlier measurements (*center*) made at CERN and at Brookhaven National Laboratory (BNL) were unable to reach this level of accuracy.

cold antihydrogen atoms should be formed by mixing large numbers of extremely cold antiprotons with large numbers of extremely cold positrons. In 1986 I thus outlined a program to make cold antihydrogen atoms and to confine them by their magnetic moments in a trap for neutral particles. It may also be possible to make and capture antihydrogen ions, each of which would consist of two positrons bound to an antiproton.

Several important experiments could be performed on trapped antimatter atoms. Comparisons of the internal oscillation frequencies of antihydrogen and hydrogen would test *PCT* invariance even more accurately. It might also be possible to measure directly the gravitational properties of the antimatter atom, which would be electrically neutral and hence not extraordinarily sensitive to stray electrical forces.

Antihydrogen production is an ambitious and difficult undertaking that will take some time to realize. Estimated production rates are very low. Techniques must be devised to cool antihydrogen to the low energies required for trapping—conventional cooling methods involve collisions with cold surfaces, which would cause antihydrogen to annihilate. It also remains to be shown that accurate spectroscopic measurements can be done with only a few atoms in a trap. One very encouraging circumstance is that antihydrogen is more easily detected than hydrogen. Pions emitted on annihilation record the presence of a single antihydrogen atom.

Contemplated antihydrogen production requires the largest possible number of cold antiprotons. To this end, we have demonstrated that we can "stack" antiprotons harvested from successive LEAR pulses. Instead of ejecting the cold electrons from the trap once the antiprotons from one pulse have been stored, the electrons are used to cool the antiprotons from many successive pulses. In this way, during one hour, more than 100,000 cold antiprotons have been stacked, or added to one another, in the trap. We estimate that our current apparatus is capable of capturing and cooling up to one million antiprotons. It should be possible to employ a larger trap and higher trapping voltages to capture and cool an even larger number of antiprotons.

It is always difficult to predict what will transpire at a frontier just beginning to be explored. Whatever experiments are done with cold antiprotons, however, they are likely to be small, tabletop investigations especially suited for students to carry out as part of their training. Perhaps the antiprotons will even be transported away from their source. At present, we skim only a small fraction of the available antiprotons from the huge high-energy experiments for which the antiproton sources were constructed. In the future, large, high-energy experiments will use protons instead of antiprotons. A major challenge will be to retain access to an antiproton source so that work with cold antiprotons may continue.

FURTHER READING

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