

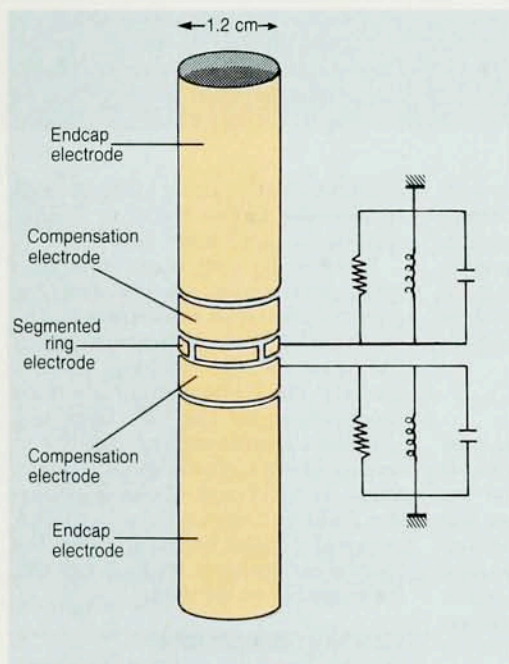
ANTIPROTONS COOLED TO 4 K AND WEIGHED IN A PENNING TRAP

Any Lorentz-invariant local field theory must obey the *CPT* theorem. That is to say, the theory must be invariant under the *combined* operations of charge conjugation, parity inversion and time reversal, even though we know that these symmetries, taken one at a time, can be violated in elementary-particle processes. It follows that particles and their antiparticles must have identical masses and equal magnetic moments (of opposite sign).

For electrons, the best demonstration of the *CPT* theorem to date is the comparison of the gyromagnetic ratios g of the electron and positron by Robert Van Dyck, Paul Schwinberg and Hans Dehmelt at the University of Washington in 1987. Confining single electrons and positrons in a Penning trap of the kind with which Dehmelt and his protégés have carried out many prodigious experiments over the years, they found that the positron's g differs from that of the electron by less than 2 parts in 10^{12} . (See the story on Dehmelt's Nobel Prize in *PHYSICS TODAY*, December 1989, page 17.) Only the neutral K-meson system, with its extraordinary oscillations between particle and antiparticle, has provided a more precise test of the *CPT* theorem.

The baryons, however, have never been subjected to a very precise scrutiny of *CPT* invariance. All the baryons, of which the proton and neutron are the lightest, contain three quarks. It is quite reasonable to ask whether these three-quark composites might violate symmetries respected by the quarkless electron or by the mesons, which are quark-antiquark states. But as recently as three months ago, the best one could say about *CPT* invariance among the baryons was that the mass of the antiproton differed from that of the proton by no more than 5 parts in 10^5 . It was even noted that the antiproton appeared to be lighter by one standard deviation.

All this changed quite abruptly at the April meeting of The American



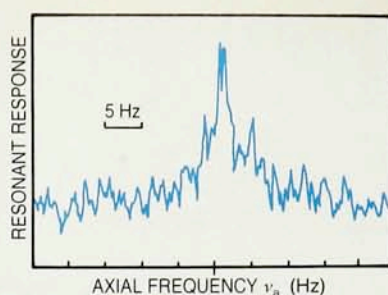
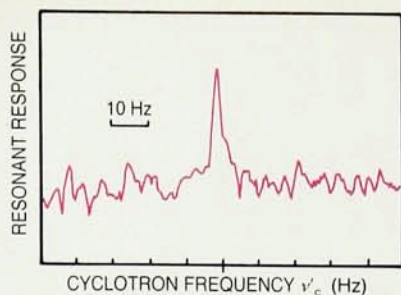
Antiproton trap¹ is an open-geometry modification of a Penning trap, with the usual five hyperboloid electrodes replaced by a stack of five cylinders. The electrodes produce a quadrupole field that forms a tiny axial harmonic potential well at the center. The trap sits in a strong axial magnetic field. Tuned LCR circuits are coupled to a compensation electrode and to one segment of the ring electrode. They can drive, detect and cool the oscillatory modes of the trapped antiprotons.

Physical Society in Washington, DC, where Gerald Gabrielse reported that his Harvard group and their collaborators from the Universities of Mainz and Washington had achieved a thousandfold improvement in our knowledge of the antiproton mass. Bringing a Penning trap to CERN to catch and store antiprotons from the LEAR low-energy antiproton ring, they have shown¹ that the inertial masses of the proton and antiproton differ by less than 4 parts in 10^8 .

In addition to its interest for the physics of elementary particles, this result highlights the remarkable evolution of the Penning trap as a high-precision mass spectrometer for atomic and molecular ions in recent years, thanks largely to the work of Van Dyck's University of Washington group. They have measured² the proton's atomic mass to 3 parts in 10^9 and the proton/electron mass ratio to 2 parts in 10^8 . The current record is claimed by David Pritchard's group at

MIT. Last fall they reported³ a measurement of the mass ratio of the molecular ions CO^+ and N_2^+ to 4 parts in 10^{10} . With this level of precision, corresponding to 10 eV, the day is approaching when it will be possible to "weigh" chemical bonds.

Gabrielse and company hope to achieve a precision of 10^{-9} in a year or so with their antiproton trap. But during the past year most of the group's effort⁴ has gone into cooling the antiprotons by ten orders of magnitude from the 6-MeV kinetic energy at which they are delivered by LEAR. Antiprotons pose all sorts of special problems. They have to be produced at high-energy accelerators, which means that they begin life with far too much energy for precision measurement. And then when they are finally cold enough, antiprotons have enormous annihilation cross sections, so that one needs unprecedented vacuum levels to keep them stored in the trap. Furthermore, the magneti-



Cyclotron resonance (left) and axial harmonic resonance (right) appear as very narrow peaks in these typical spectra of the radiofrequency microvoltages induced across the resistors in the tuned circuits of the antiproton trap¹ by the oscillatory motions of the trapped particles. The antiproton mass measurement comes principally from the precise location of the cyclotron resonance, whose linewidth is only a few parts in 10^8 of its 90-MHz frequency. The frequency of the axial harmonic resonance, required for a correcting term in the mass measurement, is near 2 MHz.

cally noisy milieu of a large accelerator complex poses daunting problems of shielding for those whose measurements require a very strong magnetic field that is rigorously uniform in space and time. Gabrielse hopes soon to carry stored antiprotons away to quieter precincts.

Penning traps

The traditional Penning trap is best known for exquisite measurements with single electrons stored for remarkably long times. Gabrielse and Dehmelt once kept a lone electron stored for ten months in the process of demonstrating a delicate relativistic hysteresis effect. (See *PHYSICS TODAY*, May 1985, page 17.) The electron is confined in a roughly cylindrical trap, about a centimeter across, bounded by five electrode surfaces. The surfaces of the two endcap electrodes and the central ring electrode are carefully machined hyperboloids of revolution. Together with the two compensating electrodes flanking the central ring, they provide the weak electric quadrupole field that constrains the trapped electron in the axial direction.

The much stronger transverse confinement of the charged particle (or particles) is provided by a strong, uniform magnetic field parallel to the axis, generated by a superconducting solenoid that surrounds the Penning trap. The trap is maintained at liquid helium temperature (4 K). A charged particle confined in such a trap simultaneously executes three independent modes of oscillatory motion: In the transverse plane, the particle executes small, high-frequency cyclotron orbits around the magnetic field lines, as well as larger magnetron orbits at much lower frequency. At an intermediate radio frequency, the particle

oscillates harmonically along the axis in response to the restoring component of the quadrupole field.

When a Penning trap serves as a mass spectrometer, the cyclotron frequency (with small corrections for the other modes) is the inverse measure of the mass of the orbiting particle species. The traps used for ion mass spectrometry by the Van Dyck and Pritchard groups are very similar in configuration to the original electron traps. The Harvard-Mainz-Washington Penning trap, on the other hand, required a major departure from the traditional design to make it suitable for trapping antiprotons.

Catching antiprotons

The 20-meter-diameter LEAR storage ring is an adjunct of CERN's 26-GeV Proton Synchrotron. Antiprotons produced when the 26-GeV proton beam hits an external target are accumulated and injected backwards into the PS, where they are decelerated to a kinetic energy of 175 MeV for injection into LEAR. In the LEAR ring the antiprotons are further decelerated to 6 MeV before being sent off to Gabrielse's Penning trap in a 250-nanosecond pulse containing about 10^8 antiprotons. "6-MeV antiprotons were about the coldest anyone had ever stored," Gabrielse told us. "We had to improve on that by ten orders of magnitude."

The pulse is passed through an aluminum degrading plate near the mouth of the trap so that a small fraction of the antiprotons become slow enough (less than 3 keV) to get caught. To provide access for the antiprotons, the trap is a 13-cm-long open stack of five consecutive 1-cm-diameter cylinders, replacing the five electrodes of the traditional, closed

Penning geometry. (See the figure on page 17.) Antiprotons traversing the length of the trap run into a 3-kV potential barrier at its downstream end. The overwhelming majority are fast enough to jump the barrier and leave the scene. The few thousand whose energy has been degraded below 3 keV are reflected back through the row of cylinders. But by then the trap has been sprung: A new potential barrier has appeared at its entrance, barring this way out. Raising a 3-kilovolt barrier in the 15 nanoseconds available between the last antiproton arriving from LEAR and the first one bouncing back is an electronic feat requiring a krytron, a tiny vacuum tube of the kind used to trigger nuclear weapons.

Waiting for these trapped antiprotons is a tiny cloud of very cold electrons, confined in a volume of less than a cubic millimeter in the middle of the trap by a harmonic potential well 50 eV deep. The electrons have been cooled to the 4-K ambient temperature of the trap by synchrotron radiation loss as they orbit in its 6-tesla axial magnetic field. As the trapped antiprotons traverse the cold electron cloud again and again, they are soon cooled to the same temperature.⁴ At this point the electrons, having served their purpose, are expelled from the trap by rf resonant excitation of their axial oscillation in the little harmonic well, which has been raised to a depth of only 1 volt. The 3-kV end barriers have by this time been removed.

With the cooling electrons gone, one is left with several thousand antiprotons with an average kinetic energy of less than a milli-electron volt. One can reduce this population simply by gradually making the harmonic potential well shallower. The leaking antiprotons signal their departure by annihilating with ordinary matter outside the vacuum to produce pions, which are recorded with scintillation counters. In principle, a lone antiproton would yield the most precise mass measurement, because it would minimize problems of space charge, image charge and magnetic-field inhomogeneity. That is the group's eventual goal. But at this stage, Gabrielse told us, other uncertainties still dwarf the benefits of drastic population reduction. The group has measured the mass with as few as 20 antiprotons in the trap, and as many as 20 000, without discerning any population dependence.

Mass measurement

The "free space" cyclotron frequency ν_c of a particle of mass M and charge e orbiting in a uniform magnetic field B

COBE Photographs the Milky Way in Infrared



Would you believe that this is our own Milky Way? It is not an artist's conception of what the Galaxy might look like to an outside observer, but rather a near-infrared image of the inner reaches of the Milky Way, produced by the Diffuse Infrared Background Experiment aboard the Cosmic Background Explorer satellite. COBE has been in Earth orbit since November. (See *PHYSICS TODAY*, March, page 17.)

DIRBE looks at the infrared sky through ten different filters, ranging in wavelength from 1 to 300 microns. Its principal purpose is to look for the diffuse infrared cosmic glow expected as a relic of the earliest generation of galaxies. To that end, DIRBE must also study the infrared emission of non-cosmological foreground objects like the Milky Way.

This picture is a superposition of the images in three near-infrared wavelengths: 1.2 μm , 2.2 μm and 3.4 μm , shown here, respectively, in blue, green and red. Thus the image appears reddest where intervening interstellar dust strongly absorbs shorter wavelengths. At visible wavelengths (below

0.78 μm), the central bulge of the Galaxy, so prominent here, is completely obscured by dust. The white dots are stars in our neighborhood.

An earlier NASA orbiting infrared observatory, the 1983 Infrared Astronomy Satellite, was restricted to wavelengths longer than 12 microns. The IRAS images of the inner Milky Way (*PHYSICS TODAY*, August 1984, page 18) were less spectacularly visual than what we see here, because at those farther-infrared wavelengths one sees less starlight and more thermal emission from interstellar dust.

This wide-angle picture, extending 96° to either side of the Galactic center, makes the center seem farther away than its actual distance of 28 000 light years. The edge of the Galactic disk, as seen here, extends over a full 180° of sky. To get a better idea of what the inner galaxy looks like from our vantage point, the reader should wrap this picture in a semicircle around his eyes like a Cinerama screen.

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simply equals $eB/2\pi M$. For a proton (or antiproton) in a 6-T field, that's about 90 MHz. But in a Penning trap one can't determine M just by measuring the cyclotron frequency, because in the complicating presence of the trap's electric quadrupole field the expression for ν_c also involves the eigenfrequencies of the axial and magnetron oscillations. In the Harvard-Mainz-Washington trap, the 11-kHz magnetron frequency (due to the $\mathbf{E} \times \mathbf{B}$ drift of the cyclotron orbits) is so much lower than the others that one need only measure the cyclotron and axial frequencies. The axial frequency is about 2 MHz.

The center of the quadrupole field is a saddle point. In the axial direction it is the bottom of a harmonic potential well, but in the transverse plane it is the top of a potential hill. One wants to keep the amplitude of the magnetron motion as small as possible, to hold the antiprotons close to the axis. This is accomplished by sideband cooling, an important tech-

nique in Penning-trap measurement developed in the late 1970s by Dehmelt, Van Dyck and David Wineland (now at the National Institute of Standards and Technology in Boulder, Colorado). In essence, one pushes the antiprotons up the transverse hill by feeding rf power into the trap at the sum of the axial and magnetron frequencies.

The trap's electrostatic field must have a very accurate quadrupole configuration, minimizing anharmonic higher components in the axial restoring force, so that the resonant frequency of the axial oscillation will be independent of its amplitude. In the conventional design, this has required laboriously machined hyperbolic electrode surfaces and a pair of compensating electrodes flanking the central ring to correct for anharmonic terms in the potential. Gabrielse and his colleagues have concluded, however, that they can achieve the same quadrupole field quality with the open configuration of stacked cylin-

ders they needed for antiproton access if the ratio of cylinder lengths is precisely chosen to meet an orthogonality condition that keeps the leading harmonic term fixed while the higher multipole terms are tuned by adjusting the electrode voltage biases.⁵ The attractive simplicity of this geometry may in fact make it the configuration of choice in future, even for less exotic ionic species than antiprotons.

The trap's 6-tesla magnetic field is also subject to demanding requirements. It must be spatially uniform, so that the cyclotron frequency will be independent of position. And if one is attempting to compare the masses of different species (in this case protons and antiprotons) to a few parts in 10^8 , the field must remain comparably stable as one trap population replaces the other. This temporal constancy is a particular problem at LEAR, where nearby powerful accelerator magnets are cycled every few seconds. Furthermore, conventional magnetic

shielding is of little use at 6 T.

To assure the requisite constancy, Gabrielse and company have incorporated special induction coils into the superconducting solenoid that provides the 6-T field. The time dependence of ambient magnetic fields induces correcting currents in these coupled coils. The group finds that they can in this way screen out the undesirable external fields by a factor of about 150. This new self-shielding solenoid design should also prove useful in magnetically quieter environments, where the nearest elevator or subway is the main problem. Gabrielse has in fact called the record precision claimed by Pritchard into question,⁶ arguing that the MIT group's laboratory may be magnetically noisier than they think. In reply, the MIT group has written that "our measurements on our solenoid show that it shields three times better than Gabrielse's estimate."⁷

"And furthermore," Pritchard told us, "we're $\sqrt{2}$ times further from the Cambridge subway line than he is."

Listening in

The oscillating antiprotons induce voltages across two resonant, tuned LCR circuits coupled to the trap. One circuit is coupled to their cyclotron motion by way of a segment of the central ring electrode. The other couples to their axial oscillation via one of the electrode cylinders flanking the ring. These external circuits serve to cool, excite or listen in on the motion of the antiprotons, as the occasion warrants.

The oscillations are cooled to the liquid helium temperature of the external resistors in the tuned circuits by ohmic dissipation. This "resistive cooling" is what keeps the antiprotons cold after the electrons have been expelled. It works so well that "it seems that we can store these cryogenic antiprotons indefinitely," the group reports.¹ They find the mean lifetime of a stored antiproton to be at least 15 weeks. Given the annihilation cross section of low-energy antiprotons (greatly augmented by atomic polarization mechanisms), it follows that the trap has fewer than 100 residual background gas molecules per cubic centimeter, a vacuum so good that it would be almost impossible to measure without the antiprotons.

The tuned circuits are also used to excite either mode by driving it near resonance. "Then we turn off the drive," as Gabrielse describes it, "and simply sit back and listen to the antiproton radio." The electrodes now serve as antennae to pick up the

rf radiation of the antiprotons near the resonant cyclotron and axial frequencies. A spectrum analyzer records the power spectra of the tiny voltages induced across the resistors of the coupled circuits by the oscillating antiprotons. The figure on page 18 shows typical results. The very prominent resonant peaks are only a few hertz wide.

To determine the antiproton/proton mass ratio, one doesn't need to know the magnetic field intensity very well, except to be certain that it remains sufficiently stable while one measures the resonant frequencies first with one species and then the other. The free-space cyclotron frequency, which goes precisely like $1/M$ for fixed B , is given in adequate approximation by

$$\nu_c = \nu'_c [1 + \frac{1}{2}(\nu_a/\nu'_c)^2]$$

where ν'_c and ν_a are the cyclotron and axial frequencies actually measured in the Penning trap.

The Harvard-Mainz-Washington group's reported result is

$$M_p/M_p = 0.999\,999\,977(42)$$

where the number in parentheses is the uncertainty of the last two significant figures. This result is certainly in accord with the earlier measurements, but it claims a thousand times greater precision.

This new result is an average over five separate measurements, which showed a spread of less than 2 parts in 10^8 . The experimenters estimate that their systematic errors are significantly smaller than this spread. One such systematic effect, the frequency shift due to image charge induced on the electrodes, could be reduced by decreasing the antiproton population. But because the antiproton trap is considerably larger than traditional Penning traps, the group concluded that this effect was much smaller than the random variation from measurement to measurement. The quoted uncertainty of 4 parts in 10^8 includes the finite linewidth of the cyclotron resonance.

Things to come

This was of course a measurement of inertial rather than gravitational mass. The possibility remains that the gravitational masses of the proton and antiproton differ by much more than 4 parts in 10^8 . But because gravity is so much weaker than the Coulomb force, it is extremely difficult to carry out a free-fall experiment with naked protons and antiprotons. The smallest stray electric field could be fatal. Nonetheless, that is

essentially what a collaboration headed by Michael Holzschneider (Los Alamos) is planning to do at LEAR. Gabrielse and his colleagues, on the other hand, are hoping eventually to measure the gravitational mass with neutral antihydrogen atoms.

Even outside the exotic realms of antimatter, the prospects for high-precision ion mass spectrometry in a Penning trap are intriguing. By measuring a species together with carbon-12, one can get its mass directly in atomic mass units. With precision at the level of electron volts, one can weigh the difference between different chemical bonds. One can also, in effect, weigh photons emitted in nuclear transitions from metastable states by comparing the masses of excited and ground-state nuclei. Taken together with a direct measurement of the photon's wavelength, this would yield a precise new determination of Avogadro's number times the Planck constant. That would be a major step toward replacing the platinum kilogram kept under glass in a Paris suburb, the last of the artifact standards, with an atomic definition of the gram.

The new spectrometry should even help to ascertain the mass of the (electron) neutrino. The best upper limit we now have on the neutrino mass (17 eV with 95% confidence) comes from examining the end point of the beta-decay spectrum of tritium. A new Penning-trap determination of the mass difference between tritium and helium-3, the daughter nucleus, would be a great help for measurements of this kind.

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