Precision Mass Spectroscopy of the Antiproton and Proton Using Simultaneously Trapped Particles

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This last of a series of three measurements improves the comparison of antiproton $(\bar{p})$ and proton (p) by almost a factor of 10^6 over earlier exotic atom measurements, and is the most precise CPT test with baryons by a similar large factor. Measuring the cyclotron frequencies of a simultaneously trapped $\bar{p}$ and H^- ion establishes that the ratio of q/m for $\bar{p}$ and p is $-0.999\,999\,999\,91 \pm 0.000\,000\,000\,09$, more than 10 times the accuracy over our previous measurement. This 9×10^{-11} comparison makes the first use of simultaneously trapped particles for sub-ppb spectroscopy. [S0031-9007(99)08869-9]

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The first comparison [1] of the antiproton $(\bar{p})$ and proton (p) established the discovery of the $\bar{p}$. Later comparisons, deduced from measurements of x-ray transition energies for $\bar{p}$ orbiting as "heavy electrons" in exotic atoms [2–4], attained a fractional accuracy of 5×10^{-5}. In this Letter, we report the last of a series of three comparisons of the charge-to-mass ratios for $\bar{p}$ and p. Together these improve upon the exotic atom measurements by nearly a factor of 10^6 (Fig. 1a), and this third measurement improves our second by more than a factor of 10 (Fig. 1b). The three comparisons each involve $\bar{p}$ accumulated at 4.2 K using the slowing, trapping, cooling, and stacking techniques developed by our TRAP collaboration [5,6] to reduce by 10^{10} the energy of $\bar{p}$ from the unique Low Energy Antiproton Ring (LEAR) at CERN. Charge-to-mass ratios, q/m, are deduced from cyclotron frequencies, $\nu_c = qB/(2\pi m)$, in a magnetic field B. The first [7] used 100 trapped $\bar{p}$ and p for a 40 ppb comparison (1 ppb $= 10^{-9}$). The second [8] used individually trapped $\bar{p}$ and p to attain a 1 ppb comparison accuracy.

Two new features of this third comparison of q/m for $\bar{p}$ and p allow us to attain a 90 ppt accuracy (1 ppt $= 10^{-12} \approx 1$ meV). First, an H^- ion is used in place of a p to eliminate the most important systematic uncertainty of the previous measurement (see below). The measured $\nu_c(H^-)$ is simply converted to $\nu_c(p)$ using

$$\nu_c(p) = 1.001\,089\,218\,750\,(2)\,\nu_c(H^-)\,. \qquad (1)$$

The conversion adds no uncertainty to our measurement since the 0.1% correction from the electron-to-proton mass ratio [9], the 14 ppb correction for the H binding energy, and the 0.8 ppb correction for the H^- electron affinity are all known much more accurately than needed. The second new feature is that the $\bar{p}$ and H^- are in the same trap at the same time. Oscillation frequencies of one particle are measured while it has a small cyclotron radius, and the other is "parked" in a cyclotron orbit large enough to produce no detrimental effect at our accuracy. (The alternative of two trapped ions sharing a magnetron orbit was used to demonstrate much less precise mass spectroscopy [10], but has not led to the predicted improvements in accuracy.) Our accuracy is comparable to the most precise mass spectroscopy of conventional ions in environments more favorable than that of an accelerator hall [9,11].

The new comparison is the most precise test of CPT invariance made with baryons by approximately 6 orders of magnitude. C, P, and T represent the charge conjugation, parity, and time reversal transformations, respectively. The invariance of physical laws under the combined transformation CPT is widely assumed to be true, despite violations of C, P, and T separately. The Lorentz invariant, local field theories that describe all interactions but gravity are invariant under CPT [12]. The most recent speculations about CPT violations have arisen in the context

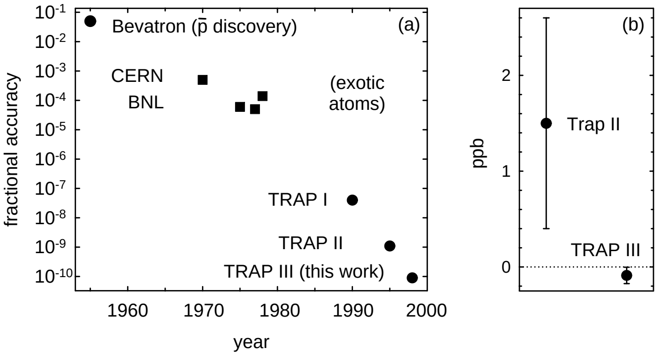

FIG. 1. (a) Accuracy in comparisons of $\bar{p}$ and p. (b) The measured difference between $|q/m|$ for $\bar{p}$ and p (TRAP III) is improved more than tenfold.

of string theory [13,14]. *CPT* invariance implies that the magnitudes of the inertial masses, charges, mean lives, and magnetic moments are identical for a particle and its antiparticle. Despite the fundamental importance of *CPT* invariance, precise experimental tests are scarce [15]. Only one lepton measurement (comparing the magnetic moment of e^+ and e^- [16]) and one meson mass comparison (of K^0 and $\bar{K}^0$ [17]) are of comparable or higher precision than the baryon comparison reported here. The new measurement also constrains possible violations of Lorentz invariance in a recent compilation of extensions to the standard model [18].

Our measurements take place within an "open access" Penning trap [19]. A spatially uniform, 5.85 T magnetic field is superimposed upon an electrostatic quadrupole produced by applying potentials to stacked cylindrical rings. These electrodes are gold-plated copper with an inner diameter of 1.2 cm. A cross section of the central ring electrode is represented in Fig. 2a. Careful choices of electrode lengths and applied voltages produce the high quality electrostatic quadrupole potential required to make particle oscillation frequencies as independent as possible of excitation energy. A useful orthogonality keeps the well depth from changing when electrode potentials are tuned to improve the quadrupole potential [19]. The trap is in an enclosure kept at 4.2 K by liquid helium, producing a vacuum that earlier $\bar{p}$ measurements indicated is better than 5×10^{-17} Torr [7].

A $\bar{p}$ in the Penning trap (or an H^-) oscillates in three motions [20]. The harmonic axial motion, at frequency $\nu_z = 1.149$ MHz, is along the direction of the magnetic field. The trap-modified cyclotron motion, at frequency $\nu_c' = 89.3$ MHz, is a perpendicular circular motion, as is the magnetron motion at the much lower frequency $\nu_m = 7.4$ kHz. These three eigenfrequencies determine ν_c via an invariance theorem [20],

$$(\nu_c)^2 = (\nu_c')^2 + (\nu_z)^2 + (\nu_m)^2, \tag{2}$$

independent of the leading perturbations of an imperfect Penning trap (e.g., tilts of the magnetic field and quadratic imperfections in the trapping potential). Attaining an accuracy of 90 ppt (10^{-12}) in ν_c requires that ν_c' be measured to this accuracy and that ν_z be measured to 600 ppb. Since ν_m is needed to only 1%, occasional measurements and the estimate $\nu_m \approx \nu_z^2/(2\nu_c')$ suffice.

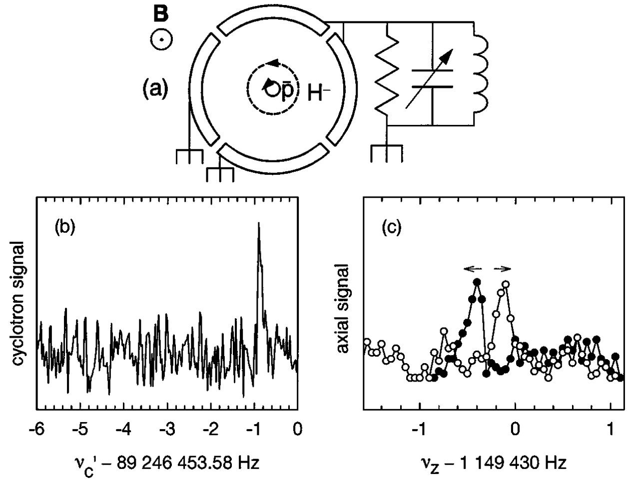

FIG. 2. (a) Central trap electrode, viewed along **B**, and the *LCR* detection circuit used to observe the signal induced by free cyclotron motion (b). Driven axial signal (c) induced across a similar circuit, as the drive is stepped up or down in frequency every 4 s, is delayed by a detector time constant. Thus ν_z (needed to ±0.7 Hz) is midway between the peaks.

The cyclotron and axial motions of a trapped $\bar{p}$ or H^- induce detectable oscillatory voltages across resonant *LCR* circuits (e.g., Fig. 2). Energy dissipation in the circuits damps these motions into thermal equilibrium with the tuned circuits near 4.2 K. To maximize signal and damping, the quality factor (Q) for each circuit is made as large as possible. The circuit resonant at ν_c' is tuned slightly with a varactor, and $Q \approx 900$. Oscillatory voltages applied to one ring section can selectively excite only one particle, since observed resonance widths are much narrower ($\ll$1 Hz) than the 10^5 Hz difference between ν_c for the two species. Special relativity shifts the cyclotron frequency [8] in proportion to the cyclotron energy E_c by a tiny but clearly observed fraction, $-E_c/mc^2 < 2 \times 10^{-7}$. Driven axial motion (Fig. 2c) is similarly detected using a superconducting inductor and shield (made of NbTi to permit operation in the large B field) with a high $Q \approx 3200$ at ν_z.

Loading a single $\bar{p}$ and H^- for measurement typically requires 8 hours, starting with a 250-ns pulse of 5.9 MeV antiprotons from LEAR. Approximately 10^3 of the 10^8 $\bar{p}$ slow below 3 keV in a degrader, are caught in the trap [5], and then cool via collisions with 5×10^5 cold trapped electrons to 4.2 K [6]. More electrons yield more cold $\bar{p}$, but the number used allows of order 500 H^- to be trapped at the same time, presumably as hydrogen atoms liberated from the degrader pick up cooling electrons. These electrons must be ejected to avoid collisions that strip the H^- and shift oscillation frequencies. They are centered with sideband cooling [20], then escape when the trap potential is repeatedly pulsed off for 200 ns, leaving trapped the more massive $\bar{p}$ and H^-.

To reduce the number of $\bar{p}$ and H^-, we excite their cyclotron motions with strong frequency-chirped driving pulses applied to one section of the ring electrode, then slowly reduce the trapping potential from 27 to 0.7 V. Meanwhile, strong noise-broadened drives increase the axial energy of any contaminant electrons and negative ions, encouraging them to leave the trap. We resolve the relativistically shifted cyclotron resonances of the few remaining $\bar{p}$ and H^-, and selectively drive their cyclotron motions until only one $\bar{p}$ and one H^- remain trapped. One of these is then excited to a large cyclotron orbit. The other is centered for measurement via sideband cooling [20]. (Slow modulations of the trapping potential permit sideband cooling even when ν_z is temporarily shifted.) An improved technique for expelling electrons from the trap increased the lifetime of a trapped H^-, but generally not beyond 1 day, although we have been able to keep a $\bar{p}$ trapped for months. (On two occasions we kept a $\bar{p}$ and H^- together for 5 days.) We presume that energetic H^- ions are stripped via collisions with undetected electrons in large orbits, a loss mechanism not available to a $\bar{p}$. In our measurements of relativistic decay curves (e.g., Fig. 3), we do not see the distortions that occur when even a single electron is near the trap center.

A measurement begins with a pulsed excitation of the inner particle to a cyclotron energy $E_c \approx 200$ eV and radius of 350 μm. Energy lost to the detection circuit makes E_c decay exponentially. The relativistically shifted cyclotron frequency thus decays exponentially back to an unshifted value (Fig. 3a) which can be extracted from an exponential fit. Occasional excitation pulses (three are shown in Fig. 3b) keep the outer particle in a large enough orbit (e.g., $E_c > 4$ keV and $r > 1.6$ mm in Fig. 3) that no shift in ν_c' or ν_z is observed as the energy of the outer particle changes. After the inner particle's cyclotron energy decays enough so that we can no longer reliably measure the cyclotron resonance, the particle positions are interchanged, using sideband cooling to remove the energy associated with the large orbit. Between four and eight cyclotron excitations, alternating between centered $\bar{p}$ and H^-, were completed during each measurement (e.g., Fig. 4), along with measurements of ν_z. The automated measurements took place during the night, when magnetic noise and drift, electrical noise, and mechanical disturbances were lowest.

Simultaneously trapped $\bar{p}$ and H^- (with nearly the same q/m) avoid systematic uncertainties of concern in a direct comparison of $\bar{p}$ and p (which differ in the sign of q/m). Before $\nu_c(p)$ could be measured in the earlier experiment [8], the $\bar{p}$ had to be ejected from the trap and the trapping potential reversed. Patch effects on the electrodes prevented an exact reversal of this potential, with the result that $\bar{p}$ and p resided at locations separated by up to 50 μm. Despite a meticulously tuned magnetic field, the field values at the location of the $\bar{p}$ and p differed by up to 1 ppb. This systematic uncertainty, and the effect of an imperfect electrostatic quadrupole, are negligible when $\nu_c(\bar{p})$ and $\nu_c(H^-)$ are compared, because the trapping potential is changed by less than 0.1%. Another substantial advantage is that the disruptive process of loading a new particle (including rapid applications of high voltages, loading and dumping large electron clouds, etc.) is avoided. Also, the $\bar{p}$ and H^- are interchanged much more rapidly, so that the magnetic field drifts less between measurements of $\nu_c(\bar{p})$ and $\nu_c(H^-)$.

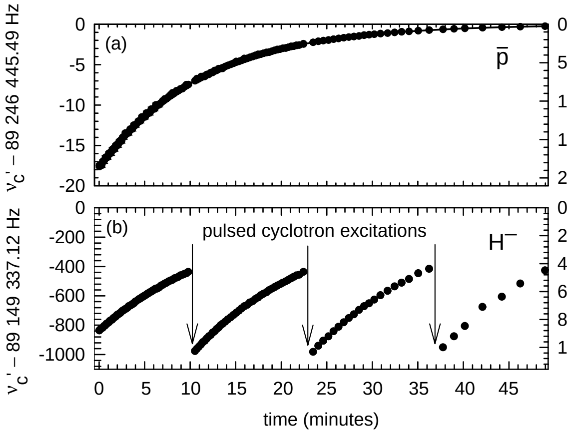

FIG. 3. (a) Special relativity shifts the cyclotron frequency of $\bar{p}$ as our detector slowly removes its energy. (b) Simultaneous signal from an H^- kept in a large orbit by three pulsed excitations.

Tiny and unavoidable drifts in the magnetic field are crucial since ν_c for $\bar{p}$ and H^- are measured at different times. External fluctuations in **B** (from nearby accelerator magnets, cranes, etc.) are reduced by up to a factor of 150 within our self-shielding solenoid [21], and by eddy currents induced in the copper vacuum enclosure. With careful regulation of the gas pressures over the helium and nitrogen dewars for the superconducting solenoid, the field drifts primarily in response to temperature changes in the accelerator hall. External magnetometers, pressure sensors, and thermometers allow us to fit only data taken while B drifts slowly enough in time to be modeled with a polynomial of order 4 or less (e.g., Fig. 4). One fit parameter is the possible difference between q/m for $\bar{p}$ and p.

For the first eight measurements, large summer temperature fluctuations in the accelerator hall produced field drifts as large as 2 parts in 10^9 per hour. We could reliably observe small cyclotron excitations with relativistic shifts of only $\Delta\nu_c = 0.3$ Hz. The cyclotron damping time was $(\gamma_c)^{-1} = 14$ min, and it took about two hours to switch between $\bar{p}$ and H^-. Fits for each measurement of six to eight cyclotron decays had χ^2_ν (per degree of freedom) as large as 2.4, and small offsets in the residuals near the end of some decay curve showed the desirability of less field drift and more rapid switching between $\bar{p}$ and H^-. Although such offsets could not mimic a difference between q/m for the $\bar{p}$ and p, we used the 290 ppt scatter in the first eight measurements, rather than the somewhat

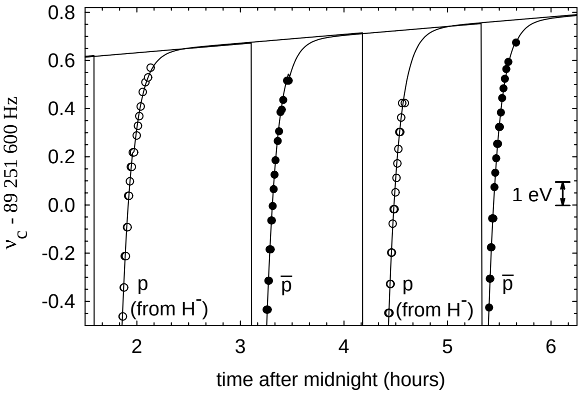

FIG. 4. Fit to cyclotron decays of $\bar{p}$ and p (from H^-) superimposed upon a slightly drifting magnetic field.

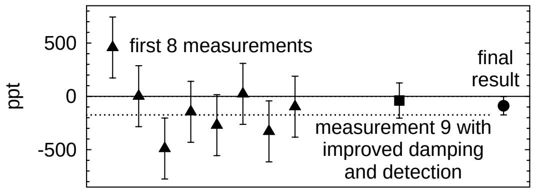

FIG. 5. Nine measurements of fractional differences in $|q/m|$ for the $\bar{p}$ and p, and their weighted average.

smaller uncertainties from the fits, as the uncertainties for these measurements (Fig. 5).

For measurement nine, smaller autumn temperature variations and better regulation of the dewar pressure reduced the field drift to 4×10^{-10} h^{-1}. Increased coupling between the cyclotron motion and the *LCR* circuit, and reduced circuit capacitance, improved the signal to noise and damping. Cyclotron excitations with $\Delta\nu_c = 0.1$ Hz could be reliably detected, and we could shift between $\bar{p}$ and H^- every hour. The fit had $\chi^2_\nu = 1.0$ and the residuals showed no offsets because we better determined a smaller magnetic field drift. Unfortunately, our magnetometers showed the onset of magnetic activity after the first four decays shown in Fig. 4, and LEAR closed before additional improved measurements could be taken. Nonetheless, this short measurement alone gives a 170 ppt comparison of q/m for $\bar{p}$ and p.

The largest uncertainty is the imperfect modeling of the magnetic field drift. Other systematic uncertainties contribute much less, as can be demonstrated with great sensitivity by looking for changes during a cyclotron decay. The orbit of the outer particle is kept large enough that no shifts in ν'_c and ν_z can be observed while the outer orbit changes radius. Uncertainties due to extremely small residual magnetic gradients are also smaller as long as the appropriate sideband cooling procedure is used to cool $\bar{p}$ and H^- to the same location for measurement. A slight mistuning of our relatively low Q cyclotron detector also produces no observable shift.

A weighted average over the nine measurements (Fig. 5) thus yields a greatly improved comparison of q/m for $\bar{p}$ and p:

$$\frac{q}{m}(\bar{p}) \bigg/ \frac{q}{m}(p) = -0.999\,999\,999\,91\,(9)\,. \qquad (3)$$

The accuracy exceeds that in our previous measurement by more than a factor of 10 (Fig. 1b), 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 *CPT* violation in this baryon system. This is the most precise test of *CPT* invariance with a baryon system by many orders of magnitude.

Finally, the comparison of $\bar{p}$ and H^- also uniquely establishes the limit $r^{H^-}_{\omega_c} < 4 \times 10^{-26}$, where $r^{H^-}_{\omega_c} = \hbar\omega_c(\bar{p}) f/mc^2$ quantifies extensions to the standard model that violate Lorentz invariance, but not *CPT* [18]. 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.

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