Thousandfold Improvement in the Measured Antiproton Mass

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Comparisons of antiproton and proton cyclotron frequencies yield the ratio of inertial masses $M(\bar{p})/M(p) = 0.999\,999\,977 \pm 0.000\,000\,042$. The fractional uncertainty of 4×10^{-8} is 1000 times more accurate than previous measurements of this ratio using exotic atoms and is the most precise test of *CPT* invariance with baryons. Independent comparisons to electrons yield the mass ratios $M(\bar{p})/M(e^-) = 1836.152\,660 \pm 0.000\,083$ and $M(p)/M(e^-) = 1836.152\,680 \pm 0.000\,088$. Cryogenic antiprotons (near 4 K) stored in a Penning trap for 2 months establish directly a lifetime greater than 3.4 months.

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The inertial mass of the antiproton $M(\bar{p})$ was deduced once at CERN (Ref. 1) and three times at Brookhaven National Laboratory[2-4] (Fig. 1), from the x-ray transition frequencies of antiprotons in orbits around nuclei. Special interest was generated when one of these exotic-atom measurements yielded an antiproton mass slightly smaller than that of the proton.[2] The most accurate measurement[3] has a fractional uncertainty of 5×10^{-5} and antiprotons and protons in the same storage ring have not provided a more precise comparison.[5]

In this Letter we report a thousandfold increase in measurement accuracy for the antiproton inertial mass. The large increase is possible because antiprotons are nondestructively studied for the first time while stored indefinitely in an ion trap, near thermal equilibrium at 4 K. This is more than 10^{10} times lower than the energy of antiprotons in the lowest-energy antiproton storage ring (LEAR at CERN). The antiprotons initially come from LEAR at 5.9 MeV, slow below 3 keV in a degrader,[6,7] are caught in an ion trap,[6] and then cool via collisions with cold electrons in the trap.[8] Crucial and unique to this mass measurement are a carefully selected cylindrical trap geometry[9] (which provides both a high-quality electric quadrupole potential and the access required to initially load and cool the antiprotons) and a system of superconducting solenoids[10] (which cancels the large fluctuations in the ambient magnetic field in the accelerator complex).

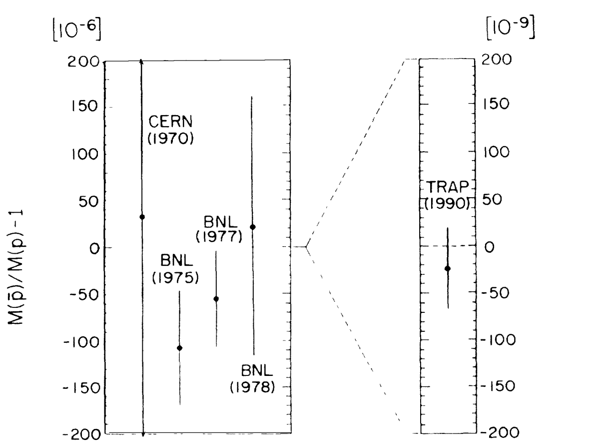

FIG. 1. Measurements of the ratio of antiproton to proton masses (Refs. 1-4). The new measurement on the right-hand side is on a scale expanded by 1000.

The new measurement is the most precise test of *CPT* invariance made with baryons, with *C*, *P*, and *T* representing charge-conjugation, parity, and time-reversal transformations. The invariance of physical laws under *CPT* transformations is widely assumed to be true, despite the possibility to violate *P*, *CP*, and presumably *T* separately, because it is not possible to construct a Lorentz-invariant, local field theory which is not invariant under *CPT*.[11] Such invariance implies that the inertial masses of a particle and antiparticle are identical, along with their mean lives and magnetic moments (except for an opposite sign for the latter). Despite the fundamental importance of *CPT* invariance, precise experimental tests are very scarce.[12] Only three lepton comparisons (of magnetic moments and masses with e^+,e^- and of magnetic moments with μ^+,μ^-) and one meson mass comparison (with $K_0,\bar{K}_0$) are of comparable or higher fractional precision than the baryon comparison reported here.

A Penning trap consists of a uniform magnetic field and a superimposed electric quadrupole potential. Trapped particles have three oscillatory motions.[13] The axial motion at ν_z is along the direction of the magnetic field. The cyclotron motion, at a higher frequency ν_c', is a circular motion in a perpendicular plane, as is the magnetron motion at a much lower frequency ν_m. For precision mass measurements, trap electrodes have traditionally been shaped along the hyperbolic equipotentials of the desired quadrupole potential. To provide the large opening needed to initially admit antiprotons before cooling, the trap used here is instead made entirely of stacked cylinders with the same inner diameters [Fig. 2(a)]. A careful choice of the lengths of the cylindrical electrodes and careful tuning make it possible to produce a high-quality electric quadrupole.[9] A key feature is an orthogonality[14] which keeps the well depth from changing during the tuning and which recently made it possible to observe a single electron in a related cylindrical configuration, with signal-to-noise ratio as good as is observed in the hyperbolic traps.[15] A good environment for a precision measurement is thereby provided, while maintaining the needed access.

The 6-T magnetic field also requires special attention owing to the need to do precision mass spectroscopy in an accelerator complex. The basic plan for the mass measurement (actually a comparison of charge to mass ratios e/M) is to compare the cyclotron frequency $\nu_c = eB/2\pi M$ of antiprotons with the cyclotron frequencies for protons and electrons. First one particle species, then the other, must oscillate in the same magnetic field. To this end, a persistent superconducting solenoid is used which produces an extremely homogeneous magnetic field that drifts at less than 8×10^{-10} per hour (after settling down for a month or two). The real difficulty is that the magnetic field fluctuates because the ambient magnetic field (in which the solenoid is located) is fluctuating. While high-frequency fluctuations are shielded by eddy currents induced in various cylindrical conductors surrounding the trap, low-frequency fluctuations are potentially very serious. These ambient fluctuations are monitored continuously with a fluxgate magnetometer,

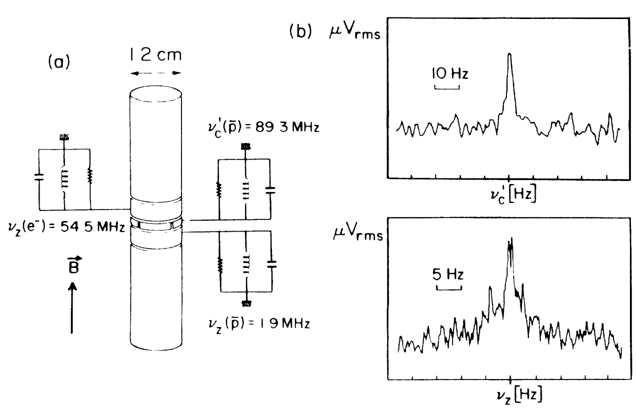

FIG. 2. (a) Trap and ac tuned circuits used to observe the axial motions of electrons (left), the axial motion of antiprotons (lower right), and the cyclotron motion of antiprotons (upper right). (b) Typical antiproton resonances.

and the magnets from the nearby CERN proton synchrotron (PS) are the largest problem, making 4-μT (40 mG) fluctuations at our location as often as every 2.4 s. The solution is to cancel such fluctuations at the location of the trapped particles by the addition of a superconducting solenoid inductively coupled to the high-field solenoid.[10] Currents induced in the coupled superconducting solenoids cancel the effect of spatially uniform fluctuations by a factor of 156, without compromising the homogeneity of the magnetic field.[16] Gradients in the fluctuating fields from nearby sources reduce the shielding of the PS fluctuations to a factor of 110 and the LEAR magnets only several meters away are shielded by a factor of 50. Nonetheless, magnetic-field stability is removed from being an issue in this measurement, as long as we monitor whether the two nearest bending magnets are on or off.

After slowing, capture, and electron cooling,[6-8] of order 10^4 antiprotons reside with approximately 10^7 electrons in the Penning trap. To selectively eject the electrons, we drive the oscillatory axial motion of the electrons, by strongly driving at both ν_z and $\nu_z+\nu_m$, and then suddenly reduce the trapping well depth in 3 ms. This process is repeated. The potential is first dropped to 4 V, then to 1 V, and then repeatedly to 0.3 V or below, depending on whether the number of antiprotons is to be reduced as well. The annihilation of antiprotons escaping from the trap is monitored by detecting charged annihilation pions in surrounding plastic scintillators. (At the end of a measurement we eject the trapped antiprotons and count their number directly using these same scintillators.) After this process, we are no longer able to detect any evidence of remaining electrons, either directly [from the oscillatory potential developed across the circuit in Fig. 2(a) tuned into resonance with their harmonic axial motion] or indirectly (via the increased damping they provide to the trapped antiprotons). The antiproton damping time changes from seconds or less when the electrons are present to hundreds of seconds when the electrons are ejected. Without electrons, the damping is due to coupling of the antiproton motion to two resonant tuned circuits [Fig. 2(a)], the first coupled to the axial oscillation and the second to the cyclotron motion, to thermal equilibrium with the resistor which is near 4.2 K. The cyclotron damping is possible because the central ring electrode is split vertically into four sections and the tuned circuit is connected to only one section.

It seems that we can store these cryogenic antiprotons indefinitely. We held approximately 10^3 antiprotons for about 2 months before deliberately ejecting them. Imprecision in our knowledge of the number of antiprotons initially loaded into the trap limits the lifetime we can set to

$$\tau_{\bar{p}} > 3.4 \text{ months}, \qquad (1)$$

but our observation is also consistent with no antiproton loss at all. 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. At the CERN Antiproton Accumulator, for example, antiprotons were recently held 11 days without adding or extracting antiprotons, with a particle loss rate corresponding to a storage lifetime of 1.4 months in the rest frame of the energetic antiprotons.[17] Based upon calculated annihilation cross sections at low energy,[18] our containment lifetime limit above requires a background gas density less than 100 atoms/cm^3. For an ideal gas at 4.2 K this corresponds to a pressure less than 5×10^{-17} Torr. The low pressure is attained by cooling the trap and its sealed container to 4.2 K.

The antiproton axial and cyclotron motions, at frequencies ν_z and ν_c', can be excited with nearly resonant, radio-frequency drives applied to the electrodes. Often, the cyclotron motion is excited instead at the sideband $\nu_c'+\nu_m$. This choice, along with a drive at the sideband $\nu_z+\nu_m$, ensures a small magnetron radius.[19] With the drives turned off, resonant responses as in Fig. 2(b) are observed. We are also able to observe the coherent axial oscillation of antiprotons (protons) which are continuously driven near resonance, but only after electrons (positive ions) are carefully expelled from the trap. This seems to be the most sensitive indication of how free the cloud of trapped particles is from contaminant species.

To deduce the cyclotron frequency $\nu_c=eB/2\pi M$ from the three eigenfrequencies in the trap, we begin with the invariance theorem[20]

$$(\nu_c)^2=(\nu_c')^2+(\nu_z)^2+(\nu_m)^2 \quad (2)$$

which is independent of the leading perturbations of an imperfect Penning trap. The magnetron frequency can be eliminated to obtain the expansion[20]

$$\nu_c=\nu_c'\left[1+\frac{1}{2}\left(\frac{\nu_z}{\nu_c'}\right)^2+\frac{9}{16}\left(\frac{\nu_z}{\nu_c'}\right)^4\theta^2+\cdots\right], \quad (3)$$

which now depends on a misalignment angle θ. However, the third term is negligible here even for θ as large as 1°, because $\nu_z\ll\nu_c'$. Thus only two frequencies [Fig. 2(b)] need to be measured to deduce ν_c, and these can be measured at the same time. Averaging over five independent sets of comparisons, wherein antiprotons, protons, and electrons were compared, we obtain

$$M(\bar{p})/M(p)=0.999\,999\,977(42)\,, \quad (4)$$

where the uncertainty in the last digits is within the parentheses. This ratio is based upon the comparisons done in the most recent and most accurate set of measurements, though many more comparisons of increasing accuracy were used to develop the technique, improve the apparatus, and study systematic effects. Figure 1 compares our measurement (on a scale expanded by 1000) with the four exotic-atom measurements.

No systematic corrections are made to obtain the quoted ratio, except for a small correction to account for magnetic-field drift (a fractional shift less than 5×10^{-9}/h) in several of the comparisons. This was required because the superconducting solenoid had to be energized shortly before the reported comparisons were made, and had not yet completely stabilized. With measurements of precision comparable to the best we obtained, we carefully tested possible sources of systematic error, including the effects of magnetic-field gradients, trap anharmonicity, an offset to the trapping potential, and possible shifts of measured frequencies depending upon the number of trapped particles. Possible effects of contaminant electrons and ions were checked carefully in additional measurements with enough contaminant particles present so that we could observe their axial-oscillation signal directly. None of these systematics produced a shift at the fractional precision of 2×10^{-8}. Because our trap is quite large, the extrapolation to 0 particles required to eliminate shifts due to image forces in smaller traps[21] is not necessary. Using half the observed cyclotron linewidth as the uncertainty, the fractional standard deviation of the five measured ratios is 3.4×10^{-8}, while the scatter in the five points is only 1.4×10^{-8}. We obtained the error quoted by adding the standard deviation for the point, the scatter, and the systematic limit in quadrature, to obtain a standard deviation which is 4.2×10^{-8} of the mass ratio.

As a check, we independently compared both protons and antiprotons to electrons. The axial frequencies of small clouds of electrons are locked to a very accurate driving frequency. Small frequency shifts, taken out by the locking circuit, are observed when the cyclotron motion is driven (at approximately 164 GHz). We obtain

$$M(\bar{p})/M(e^-)=1836.152\,660(83)\,, \quad (5)$$

$$M(p)/M(e^-)=1836.152\,680(88)\,. \quad (6)$$

An error analysis like that described above yields a comparable standard deviation for the measured ratios of 3.2×11^{-8}, but a scatter of 3.1×10^{-8} which is larger than for the antiproton-to-proton comparison. Including the same systematic limit and combining as above yields the fractional standard deviations of just under 5×10^{-8} which are quoted. The standard deviation for $M(p)/M(e^-)$ is smaller than all but the most recent measurement by Van Dyck *et al.*[22] for which a standard deviation 2.4 times smaller is reported. Our ratio clearly agrees with their $M(p)/M(e^-)=1836.152\,701(37)$ and disagrees with their earlier measurement[23] which had a systematic problem. The technique used to measure this mass ratio is similar, but differs in that no magnetic-field distortion (a magnetic bottle) is ever deliberately introduced, in that cylindrical electrodes are used rather than hyperbolic electrodes, and in that the effective size of our cylindrical trap electrodes is approximately 6 times larger than the hyperbolic electrodes used for the previous measurements. For the future, it may be easier to measure $M(\bar{p})/M(e^-)$ more accurately than $M(p)/M(e^-)$ because the $\bar{p}$ and the e^- have the same sign of charge, making it unnecessary to change the sign of the trapping potential.

In conclusion, long-term storage and nondestructive interrogation of cryogenic antiprotons has made it possible to measure the antiproton-to-proton mass ratio 1000 times more accurately than it was measured with exotic atoms. Special challenges owing to the need to begin with extremely energetic antiprotons at an accelerator complex were overcome with an open-access trap design and a self-shielding solenoid. Much higher accuracy should be possible as with positive ions,[21,24] with the time stability of the magnetic field likely to be the most serious obstacle.[25] For highest precision we may eventually move the trap apparatus, with cold antiprotons inside, away from the troublesome accelerator environment.

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