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Antiproton mass measurements

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Abstract

The most accurate mass measurements by far are measurements of charge-to-mass ratios, with the assumption that there is only one fundamental unit of charge. The most accurate of such antimatter mass measurements, by orders of magnitude, is an extremely high precision comparison of the charge-to-mass ratio of the antiproton and proton. Mass measurements with antimatter particles require the solution of unique problems—owing to the need to obtain the antimatter from unusual sources, and because antimatter particles annihilate upon interacting with matter. For the future, the most accurate antimatter mass measurements are likely to arise from even more accurate comparisons of the frequency of laser transitions of antihydrogen and hydrogen. The techniques to slow, trap and cool antiprotons that were developed to make the q/m measurements possible, have now made it possible to produce slow antihydrogen, an important step toward the eventual laser spectroscopy of antihydrogen.

Keywords: LEAR; Antiproton; Antibaryon; Antiquark

1. A 10^{10}-fold energy reduction for antiprotons from CERNs low energy antiproton ring

Without extremely cold antiprotons, no accurate measurements of the antiproton mass can be made. Developing and demonstrating a method to obtain extremely cold antiprotons was quite an adventure [1]. Since a detailed review is available [2], only a quick summary is given here.

Before the experiments of our ATRAP Collaboration, the lowest energy antiprotons – 5.3 MeV – were produced by the low energy antiproton ring (LEAR) of CERN. CERN had great reason to be proud of this unique facility—a decelerator able to slow and cool antiprotons, and deliver them to experiments, at an energy far below the GeV energies at which antiprotons were produced.

To us, however, the antiprotons from LEAR were much higher in energy than we required to measure q/m for the antiproton, and for producing cold antihydrogen. An energy reduction by more than a factor of 10^{10} was required, taking the antiprotons from 5.3 MeV down to 0.3 MeV, the average energy for thermal equilibrium at 4.2 K.

The first visit to the CERN Laboratory in Geneva, Switzerland, to propose that we measure the charge-to-mass ratio of the antiproton to a part in 10^9 or better did not go well, for three reasons:

- There was great skepticism about our proposal to reduce the LEAR antiproton energy by more than 10 orders of magnitude.
- There was skepticism about whether we could isolate and nondestructively detect a single stored antiproton.
- The sub parts per billion accuracy with which we proposed to measure the antiproton q/m was many orders of magnitude higher accuracy than was typically realized at CERN.

We were thus initially granted only a single, 24 h opportunity to prove that we could slow antiprotons down to keV energies. When this worked [3,1], then we were granted a second 24 h opportunity to prove that we could trap antiprotons at sub-keV energy. Remarkably, this also worked [4,1]. The skeptical folks at CERN turned into strong advocates for our unique, extremely low energy antiproton experiments. We were given a dedicated beam line at LEAR for our antiproton q/m measurements. When LEAR shut down, the antiproton decelerator (AD) ring was built to allow cold antihydrogen studies which are still underway.

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The 5.3 MeV antiprotons from LEAR and from the AD travel to experiments in a pulse that is typically 80 ns in duration. The crucial steps to transforming them into useful, 0.3 meV antiprotons are:

(1) Slowing the $\bar{p}$ in a matter degrader [3].
(2) Capturing the $\bar{p}$ in a Penning trap by rapidly applying a trapping well while the $\bar{p}$ are inside the trapping volume [4].
(3) Electron-cooling of trapped $\bar{p}$ [5].
(4) Stacking $\bar{p}$ from successive $\bar{p}$ injection pulses [5,2,6].

Some of these techniques were duplicated by others some years later [7]. Now, the three collaborations working at the AD all rely upon these techniques for their antihydrogen experiments and aspirations. The stacking technique, in which $\bar{p}$ from successive pulses of $\bar{p}$ from the storage ring are accumulated, was the only way to accumulate more than about 2×10^4 $\bar{p}$ for ongoing $\bar{H}$ experiments. Accordingly we made a careful study of what was possible [6].

The cold $\bar{p}$ are readily stored in a cryogenic vacuum system. Our completely sealed and cold vacuum system produces the best vacuum used for q/m and $\bar{H}$ experiments—so good that we needed to use $\bar{p}$ as the vacuum gauge. We held $\bar{p}$ for months awaiting collisions with background gas that would cause them to annihilate. No $\bar{p}$ loss was detected, and the uncertainty in the number of trapped $\bar{p}$ set a limit that the background pressure was less than 5×10^{-17} Torr [8]. This pressure is more than enough to allow $\bar{H}$ experiments for which the annihilation of $\bar{p}$, e^+, and $\bar{H}$ are simply not a problem. For vacuum systems that are not completely cold, the pressure will of course be higher depending upon the area and condition of warm surfaces, upon how completely the trap volume is surrounded by cold surfaces, and by how much gas has been pumped onto these surfaces.

The LEAR facility shut down after these $\bar{p}$ techniques were developed and demonstrated. The $\bar{p}$ techniques are now being used at a new storage ring – the antiproton decelerator (AD) – built at the CERN Laboratory in Geneva, Switzerland so that the envisioned $\bar{H}$ studies could be pursued. The AD replaces LEAR and two other storage rings that captured and accumulated $\bar{p}$ at high energies. With AD $\bar{p}$, and the TRAP techniques for accumulating cold $\bar{p}$, two international collaborations (soon to be three) are pursuing the mentioned objectives of precise spectroscopic comparisons of antihydrogen and hydrogen atoms. The AD sends about a hundred times less $\bar{p}$ to experiments in a single pulse of typically 3×10^7 (with 4.2×10^7 being the recent record high number). However, it sends more frequent pulses, about one every 80 s. The economy of the AD is possible because the $\bar{p}$ accumulation techniques we developed make it possible to do the accumulation in a trap at low energies, rather than in a storage ring at high energies.

2. Motivation: testing PCT invariance

A basic motivation for both the q/m and the $\bar{H}$ experiments is to test the fundamental PCT theorem. 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 also watch what the experiment and outcome look like in a mirror. We then build an apparatus and carry out a second experiment which 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 noticed that this basic tenet of physicists' faith had not been tested for weak interactions, those interactions between particles which are responsible for radioactive 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 P 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 above 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.

Now most physicists believe that reality is instead invariant under PCT transformations, the "T" standing for time reversal transformations. PCT invariance seems more well founded insofar as theorists find it virtually impossible to construct a reasonable theory which 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 below thus test whether reality is PCT invariant and establishes that any departures from this invariance must be smaller than the experimental error bars. This comparison is by far the most precise test of CPT invariance done with baryons, particles made of three quark particles or three antiquark particles. The antiproton-to-proton charge-to-mass ratio comparison thus joins an experiment with kaons (made of a quark particle and an antiquark particle) and a comparison of the magnetic moments 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

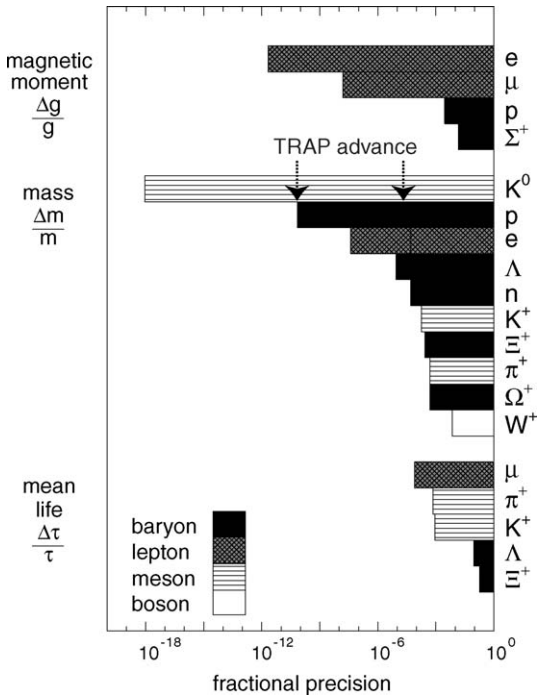

Fig. 1. Comparison of the accuracy of baryon, lepton and meson CPT tests.

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. 1. The stable particles and antiparticles in these tests come in several varieties which 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 which 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 CPT 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 an even more sensitive test of CPT invariance with leptons and baryons.

3. 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 to high energy physicists. 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 [8–10] began as soon as we produced 4.2 K antiprotons and eventually improved the comparison of antiproton and proton by approximately 10^6. Fig. 2 shows how the 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.

3.1. 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. Fig. 2 represents previous comparisons (with different techniques) along with the series of three TRAP measurements. The basic ideas for TRAP comparisons are illustrated in Figs. 3 and 4. An antiproton, proton or H^- ion makes a circular orbit in a plane perpendicular to the magnetic field direction as shown. The orbit frequency ω_c is simply re-

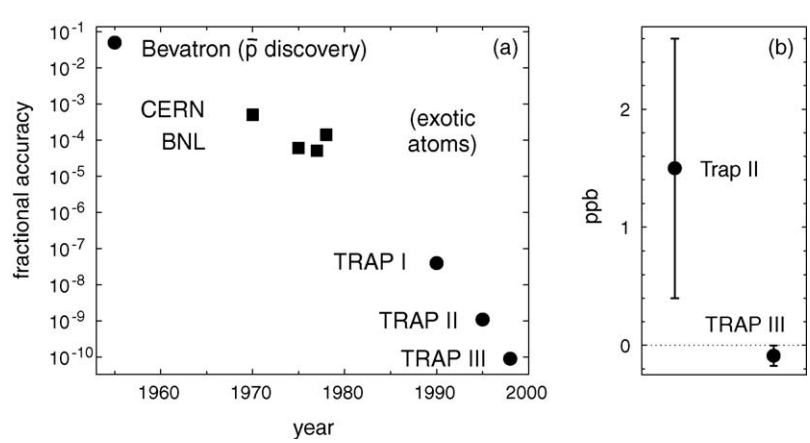

Fig. 2. (a) Accuracy in comparisons of $\bar{p}$ and p. (b) The measured difference between $|q/m|$ for $\bar{p}$ and p (TRAP III) is improved more than 10-fold (taken from [10]).

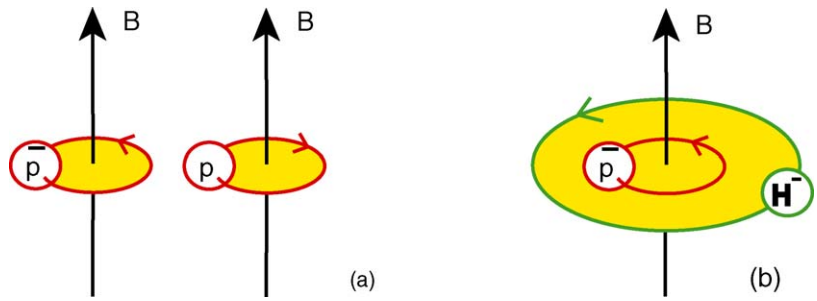

Fig. 3. (a) For TRAP I and TRAP II, antiprotons and protons are alternated in the trap. (b) For the TRAP III, a simultaneously confined antiproton and H^- ion were interchanged between larger and smaller concentric orbits.

lated to the charge of the particle q, its mass m, and the strength of the magnetic field B, by

$$\omega_c = \frac{q}{m} B. \tag{1}$$

In the strong magnetic field we use, antiprotons, protons and H^- ions make approximately 90 million revolutions per second. We detect the 90 MHz signal induced across the RLC circuit attached to the electrodes of the trap (Fig. 6) using a refined version of an FM radio receiver, and measure the oscillation frequency. The points in Fig. 2b indicates 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. The error bars indicate the measurement uncertainties.

In reality, an antiproton confined in a Penning trap follows the more complicated orbits represented Fig. 5. The small circular oscillation is the cyclotron motion discussed above 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 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 the Brown-Gabrielse invariance theorem [11]:

$$\omega_c^2 = \omega_c'^2 + \omega_z^2 + \omega_c^2. \tag{2}$$

Much of the experimental effort goes to understanding and/or eliminating any imperfection in our apparatus which 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 that the proton frequencies are measured and when 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 which 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 [13,14] (now patented [15] because of applications in magnetic resonance imaging and ion cyclotron resonance) illustrates the interplay between "pure science" and technology. Technology is pushed so hard in the pursuit of fundamental physics goals that practical applications can emerge from which have wider applicability.

3.2. TRAP I: 100 antiprotons compared to 100 protons

In our first measurement [8], the cyclotron frequency of the center-of-mass of approximately 100 antiprotons was compared to that of protons. This measurement showed that the

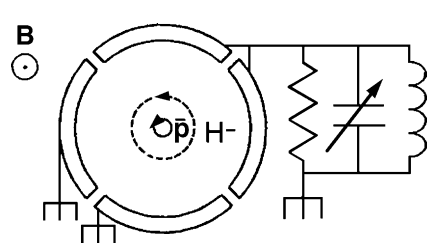

Fig. 4. The cyclotron motion induces a detectable voltage across an RLC circuit attached to a four-segment ring (taken from [10]).

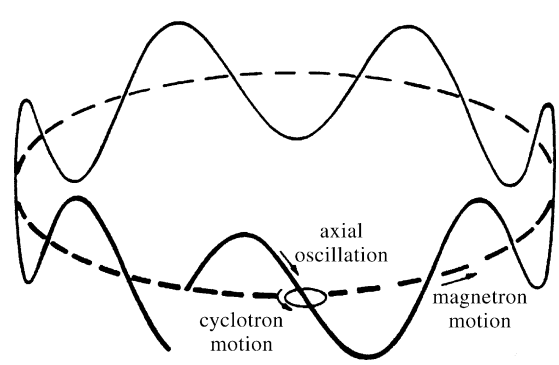

Fig. 5. Superimposed cyclotron, axial and magnetron orbit of a particle in a perfect Penning trap (taken from [12]).

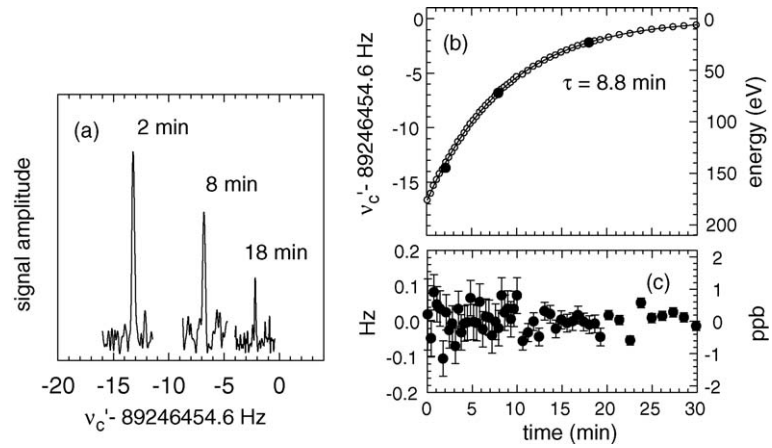

Fig. 6. Special relativity shifts the cyclotron frequency of a single trapped $\bar{p}$ as its cyclotron energy is slowly and exponentially dissipated in the detector. Cyclotron signals for three subsequent times in (a) have frequencies highlighted in the measured frequency vs. time points in (b). A fit to the expected exponential has small residuals (c) and gives the cyclotron frequency for the limit of no cyclotron excitation (taken from [9]).

charge-to-mass ratios of the antiproton and proton are the same to with 4×10^{-8} which is 40 ppb. At this accuracy the self-shielding solenoid kept the magnetic field drift to a manageable level. The improvement over earlier comparisons of antiprotons and protons using exotic atoms was more than a factor of 1000.

3.3. TRAP II: alternating one antiproton and one proton

The second mass measurement compared a single trapped antiproton to a single trapped proton [9]. The radio signal of a single antiprotons was detected nondestructively (Fig. 6a). Owing to our great resolution, this measurement provided a spectacular illustration of special relativity (Fig. 6b and c) at eV energies insofar as the antiproton's cyclotron frequency:

$$\omega_c = \frac{qB}{\gamma m} \tag{3}$$

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

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 the particle (e.g., due to the patch 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 two locations, the measured ν_c for the different species differs even if the charge-to-mass ratios do not.

3.4. 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 [10]. 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 could likely come by comparing an antiproton and an H^- ion. However, we did not initially pursue this possibility. 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 till we encountered the unavoidable disruption of an H^- ion loaded with a single antiproton. When we then did look carefully we found that we could always load negative ions during our antiproton loading. By reducing the number of cooling electrons we were able to typically load of order 500H^- 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 (Figs. 7 and 8).

This mass measurement reportes that:

$$\frac{(q/m)(\bar{p})}{(q/m)(p)} = -0.99999999991(9). \tag{4}$$

The accuracy exceeds that of the second measurement by more than a factor of 10 (Fig. 2b), 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

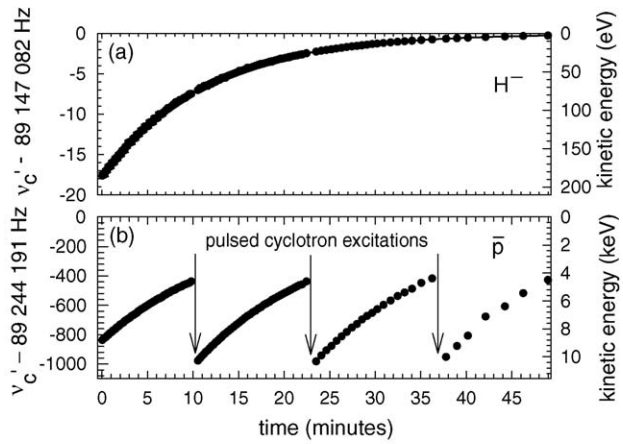

Fig. 7. (a) Special relativity shifts the cyclotron frequency of an H^- as our detector slowly removes its energy. (b) Similar signals from an $\bar{p}$ kept simultaneously in a large orbit by three pulsed excitations (taken from [10]).

CPT violation in this baryon system. This is the most precise test of CPT invariance with a baryon system by many orders of magnitude as is illustrated in Fig. 1.

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 *CPT* [16]. 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.

3.5. Slight adjustment follows the discovery of a surprising systematic shift

Small shifts in the measured cyclotron frequency of molecular ions were subsequently discovered, and then traced to the polarizability of the molecules [17]. Our most accurate q/m measurements utilized slightly polarizable H^- ions, with polarizability α, so this polarization shift must also be applied the last of our three measurements.

The surprising thing is that an effect that depends upon a motional electric field survives our careful and consistent extrapolation to zero antiproton velocity. The motional electric field $E = vB$ is proportional to the cyclotron velocity and the magnetic field. It polarizes the H^- ion, producing an electric dipole moment $d = -\alpha vB$. The resulting velocity-dependent force on the ion generates a tiny velocity-independent shift in the cyclotron frequency:

$$\frac{\Delta\omega_c}{\omega_c} = -\frac{\alpha B^2}{m} \approx 70\,\text{ppt}, \tag{5}$$

where m is the antiproton mass. The ratio of the charge-to-mass ratios of the antiproton and proton shift slightly as a result by amount that is smaller than the uncertainties that we assigned in the original report, as illustrated in Fig. 9.

Does this suggest that the magnitude of the charge-to-mass ratios of the antiproton and proton differ? It would be premature to make this conclusion insofar as the uncertainties were assigned to represent a standard deviation, and thus there is a reasonable probability that the true ratio could lie slightly outside the quoted uncertainty.

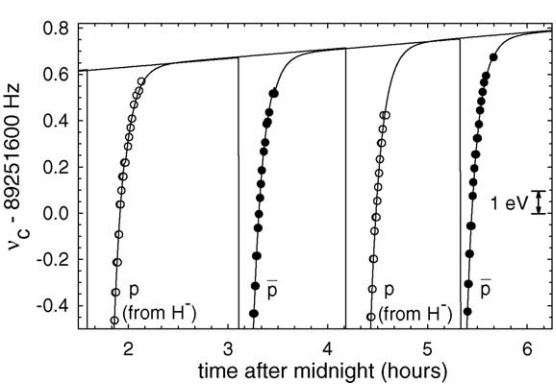

Fig. 8. Alternating cyclotron decays of $\bar{p}$ and p (from H^-) superimposed upon a slightly drifting magnetic field (taken from [10]).

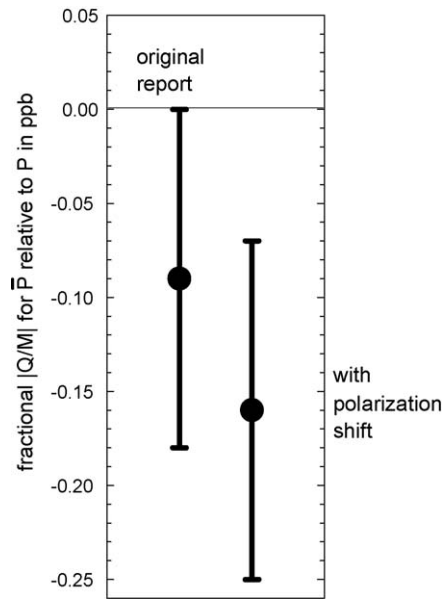

Fig. 9. Small polarization shift is smaller than the assigned standard deviation.

3.6. Possibility of a more accurate q/m measurement

A much more accurate measurement of q/m for the antiproton could certainly be carried out. This is most evident in the series of measurements (Fig. 10) that went into the final determination of q/m for the antiproton. An apparatus and technique improvement made the last 1-day measurement to be much more accurate than all of the earlier measurements. Before this new level of accuracy could be exploited, unfortunately, LEAR closed down.

A more precise measurement of q/m of the antiproton is not currently underway, but is being considered. With enough time, and a more stable superconducting solenoid, an additional order of magnitude improvement in accuracy seems feasible.

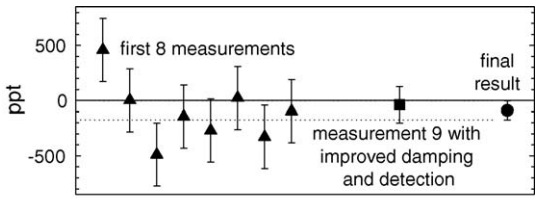

Fig. 10. Nine measurements of fractional differences in $|q/m|$ for the $\bar{p}$ and p, and their weighted average.

4. Antihydrogen

Antihydrogen spectroscopy measurements promise to be the most accurate way to look for possible differences between the positron and electron masses, and between the antiproton and proton masses. Eq. (6) shows the ratio of the Rydberg constant and the anti-Rydberg constant—quantities that one might expect to determine from measuring the 1s to 2s transition frequencies in hydrogen and antihydrogen:

$$\frac{R_\infty[\bar{H}]}{R_\infty[H]} = \frac{m[e^+]}{m[e^-]}\left(\frac{q[e^+]}{q[e^-]}\right)^2\left(\frac{q[\bar{p}]}{q[p]}\right)^2\frac{1+m[e^-]/M[p]}{1+m[e^+]/M[\bar{p}]} \quad (6)$$

Assuming that the long-range Coulomb interaction is the same in both cases, this ratio depends upon the charges and the masses of the particles from which hydrogen and antihydrogen atoms are made. Any new physics that would cause the magnitudes of the charges and masses of these ingredient particles to differ between the matter and antimatter species would thus cause the Rydberg and anti-Rydberg constant to differ.

Owing to the great accuracy with which hydrogen spectroscopy can be performed [18], and assuming that such an accuracy will eventually be attained with antihydrogen atoms as well, despite the much smaller number of available atoms [19], one could thus hope to search for much smaller deviations than has been possible with any more direct method—even the extremely accurate q/m measurements discussed earlier.

Over many years we have been working to achieve a still distant goal of precise antihydrogen spectroscopy, carried out with cold antihydrogen atoms stored in a magnetic trap [20]. This goal was firmly in mind when we invented and demonstrated the techniques for slowing, capturing and cooling antiprotons as described in an earlier section [2,1]. With this goal in mind we also invented the nested Penning trap [21–23], and developed the techniques to make antihydrogen in this device during positron cooling of antiprotons [24,22,23]. This device and method has since produced quite a large number of slow antihydrogen atoms [25–27].

However, we showed that the antihydrogen atoms detected so far [28] are moving too rapidly to catch in a magnetic trap for spectroscopy. They are also atoms which are highly excited [26,29], rather than the ground state atoms that are desired for the most accurate spectroscopy. Obtaining colder atoms in less excited internal states is the object of current ongoing antihydrogen research.

We have also demonstrated a second method for producing antihydrogen [30,31], in which lasers control resonant charge exchange collisions [32]. This second method likely produced the first truly cold antihydrogen atoms, insofar as the antihydrogen atoms are believed to be as cold as the antiprotons from which they were produced. The antiproton temperature in our experiments was close to the 4.2 K ambient apparatus temperature, but much lower antiproton temperatures should be possible using techniques demonstrated with electrons in a different set of experiments [33]. However, these antihydrogen atoms also are in highly excited states. De-exciting such atoms is again the object of ongoing antihydrogen research.

Much remains to be accomplished before accurate antihydrogen laser spectroscopy is carried out. However, we are encouraged by the progress has been made, enough to be hopeful that such measurements will eventually produce the most accurate tests for differences between the charges and masses of antiproton, protons, positrons and electrons.

Acknowledgements

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