The Aspirations to Produce Cold Antihydrogen Were Laid Out Back in 1986

Gerald Gabrielse
Erice Lecture, 1986

Recently we mentioned the possibility which we have been studying for some time, of using a nested pair of Penning traps to simultaneously capture positrons and antiprotons. ... Low [production] rates might might be sufficient to observe antihydrogen for the first time. When antihydrogen is formed in an ion trap, the neutral atoms will no longer be confined and will thus quickly strike the trap electrodes. Resulting annihilations of the positron and antiprotons could be monitored. However, it is clear that the very low rate will make further experiments with antihydrogen to be very different than experiments with copious amounts of hydrogen, and much more difficult.

For me, the most attractive way around this difficulty would be to capture the antihydrogen in a neutral particle trap as has been used for neutrons and neutral atoms. The objective would be to then study the properties of a small number of atoms confined in the neutral trap for a long time.

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PENNING TRAPS, MASSES AND ANTIPROTONS*

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Abstract

Penning traps are an important new tool for mass spectroscopy, aided by an invariance theorem which facilitates precise mass spectroscopy in an imperfect trap. The motions of particles in a Penning trap are discussed and the features which make it very attractive to do mass spectroscopy in a trap are illustrated. Careful attention is paid to the motivations and prospects for a measurement of the inertial mass of the antiproton. Prospects for such a measurement are now excellent since our TRAP Collaboration actually captured antiprotons in a Penning trap only 2 months ago. An overview of ways to cool particles within the trap is provided and brief speculations upon the possibility of producing antihydrogen in a trap are included.

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A. Motion in a Penning Trap

Consider a negatively charged particle of charge -e in a homogeneous magnetic field $B\hat{z}$. The motion is familiar cyclotron motion about a field line with angular frequency

$$\omega_c = \frac{eB}{mc}. \tag{1}$$

Such a simple system would be very nice for mass spectroscopy, since ω_c for two different ions could be measured in the same magnetic field. Although the particle is confined to a magnetic field line, however, it is free to leave the trap along the axis of the magnetic field. Also, it is not immediately clear how to measure ω_c.

Actual measurements can be performed within a slightly more complicated structure called a Penning trap, which I will describe as simply as possible, leaving details to a recent review.[1] An electrostatic quadrupole potential is added to the magnetic field using electrodes such as those shown in Fig. 1. The particles are now prevented from leaving the trap along the axis of the magnetic field because they are repelled by negatively charged electrodes above and below. The axial potential well comes at the expense of a radial potential hill which exerts an outward radial force on the particle and which must be overcome by the strong magnetic field. The added quadrupole potential modifies the simple cyclotron motion in 3 ways.

1. The cyclotron frequency ω_c is reduced to some ω_c' because the effective radial binding is reduced by the radial potential hill.
2. A harmonic oscillation is introduced along the magnetic field axis at an angular frequency ω_z.

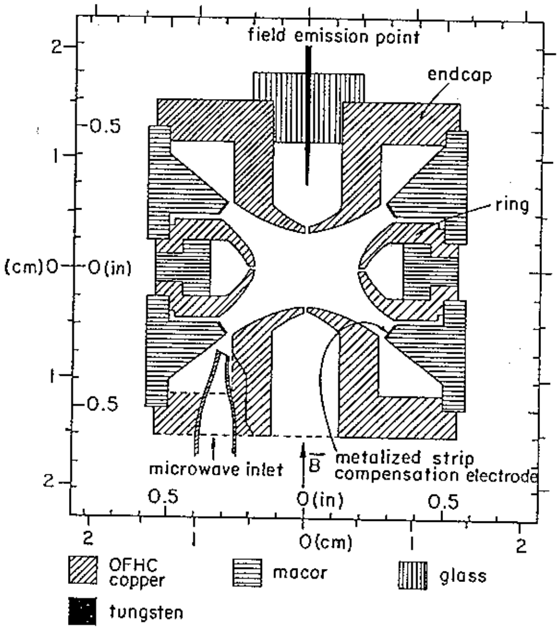

Fig. 1. Scale drawing of a Penning trap used for experiments with a trapped electron.

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[1] L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

3. The strong magnetic field and the radially outward component of the electric field together comprise a velocity filter. Particles traveling in a circular orbit at a particular velocity thus have zero net force from these two sources, independent of the charge to mass ratio. This circular motion takes place at the magnetron frequency ω_m.

For example, in a 6 Tesla magnetic field and with a 100 volts applied across the electrodes is shown in Fig. 1, a trapped antiproton has eigenfrequencies

$$\omega_c'/2\pi = 90\ MHz, \tag{2}$$

$$\omega_z/2\pi = 4\ MHz, \tag{3}$$

$$\omega_m/2\pi = 100\ kHz. \tag{4}$$

The motions can be detected via oscillatory currents induced between trap electrodes by the oscillatory motion of the trapped particles. A resistor connected between the electrodes transforms the oscillating current into an oscillatory voltage. Unavoidable trap capacitance is tuned out with an inductor so that the resistance is actually realized at only one particular resonant frequency. A sensitive amplifier across the resistor detects the oscillatory voltage. A single trapped particle can be detected nondestructively[2] as illustrated in Fig. 2. The vertical scale indicates the current detected as electrons are loaded into a trap and oscillate along the magnetic field. The horizontal axis is time and the electrons are kicked out of the trap at times indicated by arrows, by reversing the sign of the quadrupole potential for several seconds.

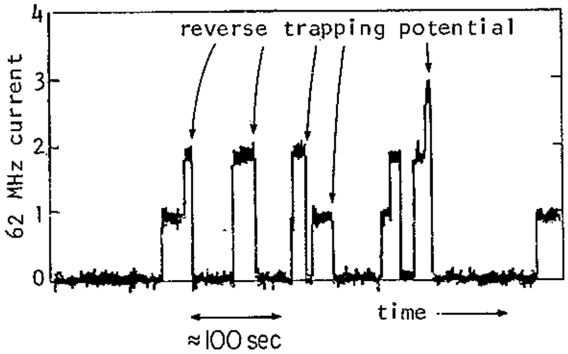

Fig. 2. Measured current induced by the ω_z motion of electrons as they enter the trap. Arrows indicate where electrons are removed by reversing the trapping potential.

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[2] D. J. Wineland, P. Ekstrom, H. G. Dehmelt, Phys. Rev. Lett. **31**, 1279 (1973)

B. Comparing Inertial Masses in a Penning Trap

In an ideal Penning trap, the cyclotron frequency ω_c can be simply deduced from measured values of the cyclotron and magnetron frequencies measured in the trap.

$$\omega_c = \omega_c' + \omega_m \tag{5}$$

Masses of 2 different particles can be compared by comparing separately measured cyclotron and magnetron frequencies, ω_c' and ω_m, measured in the same magnetic field. In the example given, Eqs. (2) - (4), the cyclotron frequency in the trap is shifted by 1 part in 10^3. In an imperfect trap, however, various imperfections shift the 3 eigenfrequencies in the trap,

$$\omega_c' \to \bar{\omega}_c' \tag{6}$$

$$\omega_z \to \bar{\omega}_z \tag{7}$$

$$\omega_m \to \bar{\omega}_m \tag{8}.$$

Fortunately, an invariance theorem proved by Lowell Brown and myself,[3]

$$(\omega_c)^2 = (\bar{\omega}_c')^2 + (\bar{\omega}_z)^2 + (\bar{\omega}_m)^2, \tag{9}$$

makes it possible to deduce ω_c in a way which is not sensitive to major trap imperfections, from the three measured eigenfrequencies in an imperfect trap. In particular, the invariance theorem is insensitive to

1. Misalignment of the magnetic field axis and the axis of the electric quadrupole potential,
2. Spatially uniform stray electric fields within the trap, since these merely shift the center of the oscillations within the trap,
3. Harmonic distortions of the electrostatic potential, such as an added potential term which goes as xy.

Since the particles are located near the center of the trap, potential distortions not covered by the invariance theorem are small, of order $(r/d)^3$ or higher, where r is the small distance from the center of the trap, d is a trap dimension and typically $r/d \sim 10^{-2}$. The trap electrodes have axial symmetry about the z axis and reflection symmetry under $z \to -z$, so that many higher order potential distortions are strongly suppressed. In addition, the leading potential distortion allowed by the electrode symmetry is explicitly tuned out[4] in a way which is quantitatively understood.[5]

Surprisingly (to me at least), the invariance theorem is not yet used for most of the mass measurements being made in Penning traps. Also, little advantage is taken of axial symmetry and high order potential distortions are typically not tuned out. I refer here to the rectangular (often cubic) trap configurations used by chemists for less precise mass measurements under the name Ion Cyclotron Resonance (ICR).[6] Complete commercial devices are available and hundreds of papers are in the literature, so it is certainly not possible to do justice to this work. Broadband amplification and

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[3] L.S. Brown and G. Gabrielse, Phys. Rev. A. **25**, 2423 (1982)

[4] R.J. Van Dyck, D.J. Wineland, P. Ekstrom and H. G. Dehmelt, Appl. Phys. Lett. **28**, 446 (1976)

[5] G. Gabrielse, Phys. Rev. A **27**, 2277 (1983)

[6] D.A. Laude, Jr., C.L. Johlman, R.S. Brown, D.A. Weil and C.L. Wilkins, in Mass Spec. Rev. **5**, 107 (Wiley, N.Y., 1986).

detection is used to detect the response of a cloud of trapped particles to an intense excitation pulse. The response is most often Fourier transformed, hence the name Fourier Transform Mass Spectrometry (FTMS).[7] An often cited "best resolution" achieved is on the order of 10^{-8} for a water sample[8] but an even higher resolution (which I will discuss presently) is claimed for the $^3H - ^3He$ mass difference. The choice of rectangular electrode geometry makes for large departures from an ideal quadrupole potential, and these deviations are especially important when the cloud of particles is highly excited to a large cyclotron radius. The axial and magnetron frequencies are typically not carefully monitored, so that no advantage can be taken of the invariance theorem Eq. (9). It is thus much harder to measure a mass accurately despite high resolution, unless mass doublets are compared. Careful studies of the effect of cloud size and distribution are carried out because these are important systematic effects.

The use of Penning traps for mass spectroscopy is relatively recent. Until recently, the most accurate mass spectroscopy was done in an RF spectrometer built by Smith.[9] A modern version of this machine[10] should compete with the accuracies now being achieved in Penning traps. However, I think that the much smaller Penning trap apparatus will eventually produce the most accurate measurements because it offers a number of advantages for mass spectroscopy. The first is that a good signal-to-noise ratio can be obtained with even a single charged particle. As an example, consider the single electron cyclotron resonance in Fig. 3. The triangular shape of this resonance has been discussed.[11] Here it suffices to observe that this resonance is present and is detected only because of special relativity, even though the electron's kinetic energy is less than 1 eV. This electron also illustrates a second advantage for mass spectroscopy in a Penning trap. Very long confinement times are possible. The electron used to produce Fig. 3 was kept for more than 10 months by itself in a Penning trap.[11] Mass spectroscopy with extremely small samples is clearly possible.

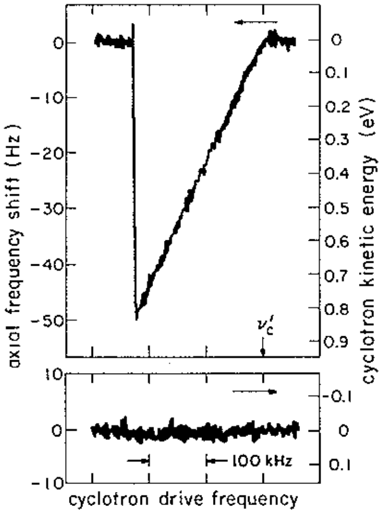

Fig. 3. Relativistic cyclotron resonance.[9]

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[7] M.L. Gross, D.L. Rempel, Science **226**, 261 (1984).

[8] M. Allemann, H.P. Kellerhals, K.P. Wanczek, Int'l. J. of Mass Spec and Ion Proc. **46**. 139 (1983).

[9] L. Smith, Phys. Rev. C **4**, 22 (1971).

[10] C. Thibault, paper contributed to this school.

[11] G. Gabrielse, H. Dehmelt and W. Kells, Phys. Rev. Lett. **54**, 537 (1985)

A third advantage for mass spectroscopy in a Penning trap is that very different masses can be measured and compared directly. In an RF spectrometer one must measure masses which are nearly equal (i.e., have the same mass number) and from a series of such mass doublets deduce a mass. In a Penning trap one can directly compare very different masses, although if narrow band detection techniques are used this requires a significant change in the tuning of the detection electronics. A good illustration is represented in Fig. 4 where progress in measurements of the ratio of the proton to electron mass M_p/m_e is shown. The upper value is from the 1973 least squares adjustment.[12] It incorporates a number of different indirect measurements of M_p/m_e. All subsequent measurements of this ratio were made using Penning traps. The next two measurements were made at Mainz[13,14] by directly comparing cyclotron frequencies in a Penning trap. Small numbers of electrons and protons were ejected from the trap to a detector and cyclotron excitations were deduced from changes in a time-of-flight spectrum. The three values from Washington[15,16,17] represents the improved accuracy which can be obtained when the particles can be kept in the trap and continuously interrogated with narrow band tuned circuits. The NBS value[18] is derived from a double resonance measurement on trapped Be^+ ions. This measurement uses calculated g values and is thus a much less direct measurement.

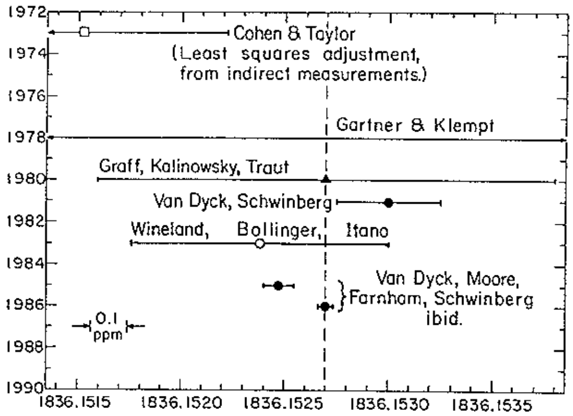

Fig. 4. Measured proton to electron mass ratio.

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[12] E.R. Cohen and B.N. Taylor, J. Chem. Ref. Data **2**, 663 (1973)

[13] G. Gartner and E. Klempt, Z. Phys. **287**, 1(1978)

[14] G. Graff, H. Kalinowsky and J. Traut, Z. Phys. **297**, 35,(1980)

[15] R. S. Van Dyck, Jr. and P. B. Schwinberg, Phys. Rev. Lett. **47**, 395 (1981)

[16] R. S. Van Dyck, Jr., F. Moore, D. Farnham and P. B. Schwinberg, Int. J. of Mass Spec. and Ion Proc. **66**, 327 (1985)

[17] R. S. Van Dyck, Jr., F. Moore, D. Farnham and P. B. Schwinberg, Bull. Am. Phys. Soc. **31** (1986)

[18] D. J. Wineland, J.J. Bollinger, W.M. Itano, Phys. Rev. Lett. **50**, 628 (1983)

The convenience of a trap for direct measurements of ion masses is also being used now to measure the masses of unstable nuclei.[19] The object is to check the nuclear mass formula with the masses of unstable nuclei and the trap offers a way to make such measurements without the need to measure a long series of doublets. The range of masses which are of interest is indicated in Fig. 5, where the accuracy desired is plotted horizontally vs. the number of nucleons, vertically. The three dashed vertical lines indicate typical nuclear energies of interest. The binding energy is of order 8 MeV/nucleon, shell adjustments contribute variations of approximately 1 MeV and nuclear pairing effects contribute of order 100 keV. For nuclei of interest, with up to several hundred nucleons (shaded region in figure), this means that a fractional mass resolution of 10^{-7} or slightly better is desired.

The fourth and final advantage I will discuss for mass spectroscopy in Penning traps is that an extremely narrow cyclotron line width can be realized, which is much narrower than that offered by other techniques. Smith's RF spectrometer[9], for example, had a linewidth of 5×10^{-5} (i.e. a resolution of 2×10^4) with 5×10^{-6} proposed for an improved version under development.[10] By contrast, linewidths much better than 10^{-8} are routinely observed with trapped electrons, positrons and protons, with resolutions as high as 10^{-10} actually observed in some cases.[20] The basic reason for the narrow line in a trap is that the trap particles occupy such a small region of space that it is relatively easy to obtain a homogeneous magnetic field over this small region. Linewidth is not the only consideration for an accurate measurement, of course. Systematic efforts and statistics will determine how much the line can be split and what accuracy can be obtained. On the other hand, those making precision measurements rarely complain about a line being too narrow.

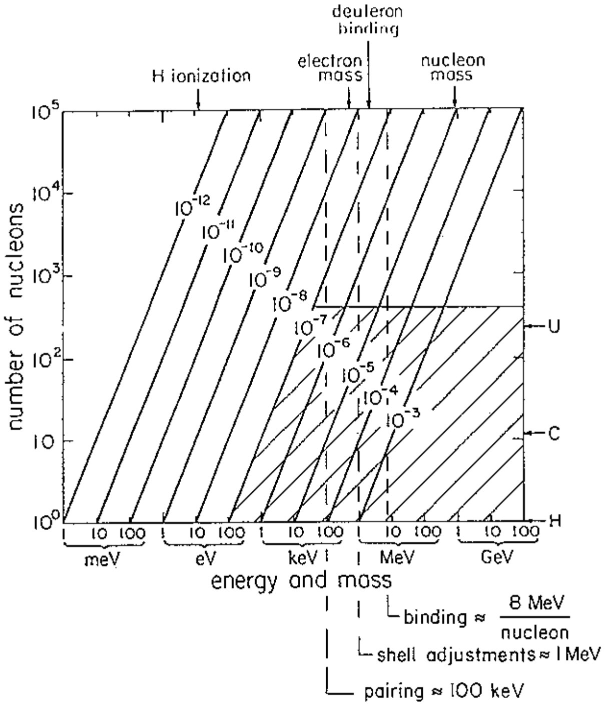

Fig. 5. Mass number versus accuracy, with shaded region of interest for nuclear physics.

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[19] Schnatz, et.al., Nucl. Inst. and Meth. (in press).

[20] R. S. Van Dyck, et al. (unpublished)

Fig. 6 illustrates the impact that mass spectroscopy in traps is already making upon the measurement of the mass difference of ^3H and ^3He. This quantity, of course, is of great interest as a part of the effort to measure the neutrino mass. The values plotted are the "adopted values" from the review by Audi, Graham and Geiger,[21] which in some cases have been adjusted from originally published values. Notice in particular the RF spectrometer values from Smith, which are uncertain at the level 5×10^{-9}. The most recent measurements by Lippman et. al.[22] are done in an ICR trap. While I personally am impressed and a bit dubious that an uncertainty of 2×10^{-9} can be achieved given the limitations of the ICR technique discussed earlier, it is clear that mass spectroscopy in traps has already contributed significantly in this case. Moreover, a group at Mainz[23] and at Washington[20] are now in the process of measuring the mass difference in Penning traps so it is very likely that greatly improved values will be presented within a year.

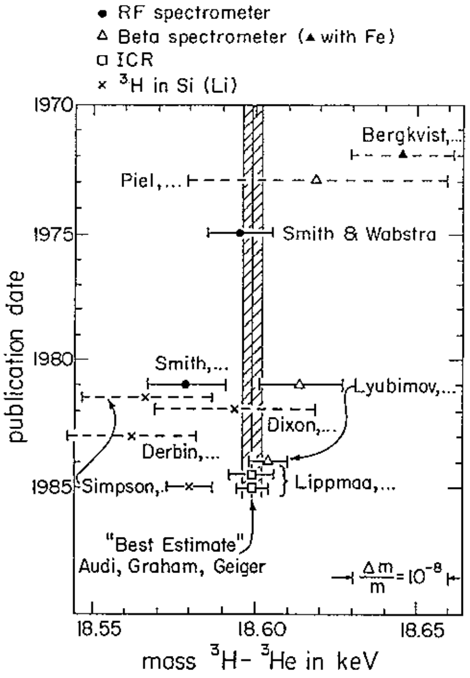

Fig. 6. "Adopted" values and uncertainties in measurements of the mass difference of ^{3}H and ^{3}He, from Ref. 19.

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[21] G. Audi, R.L. Graham, J.S. Geiger, Z. Phys. A **321**, 533 (1985).

[22] E. Lippman, et.al., Phys. Rev. Lett. **54** 285 (1985).

[23] G. Werth, et. al. (ununpublished).

C. The Antiproton Mass

Measurements of the antiproton mass[24,25,26,27] are represented in Fig. 7. All of these are deduced from measurements of the energy of x-rays radiated from highly excited exotic atoms. For example, if an antiproton is captured in a *Pb* atom, it can make radiative transitions from its $n = 20$ to $n = 19$ state. The antiproton is still well outside the nucleus in this case, so that nuclear effects can be neglected. The measured transition energy is essentially proportional to the reduced mass of the nucleus and hence the antiproton mass can be deduced by comparing the measured values with theoretical values, corrected for QED effects. The most accurate quoted uncertainty is 5×10^{-5} and is consistent with the much more accurately know proton mass, indicated by the dashed line. It looks like it would be difficult to extend the accuracy realized with the exotic atom method. It might be possible, however, that proton and antiproton masses could be compared directly in a storage ring, from the spatial separation of counter propagating beams of protons and antiprotons at comparable or somewhat improved accuracies.[28]

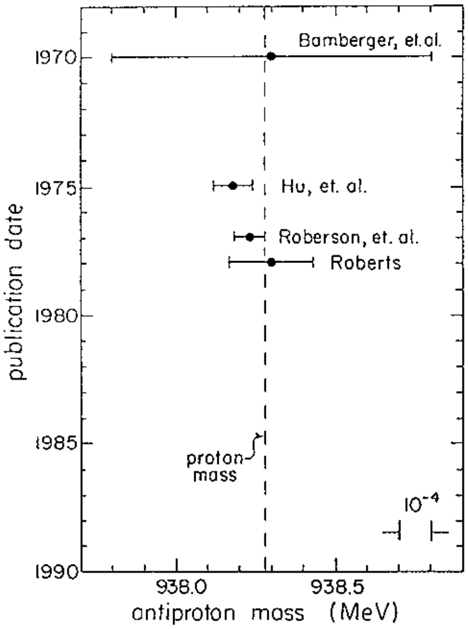

Fig. 7. Antiproton mass measurements.

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[24] A. Bamberger, et. al., Phys. Lett. **33B**, 233 (1970).
[25] Hu, et.al., Nucl. Phys. A **254**, 403 (1975).
[26] P.L. Roberson, et. al., Phys. Rev. C **16**, 1945 (1977).
[27] B.L. Roberts, Phys. Rev. D. **17**, 358 (1978).
[28] S. van der Meer, private communication.

Based upon precisions obtained with trapped electrons, positrons and protons, it seems very likely that the measurement uncertainty in the ratio of antiproton to proton masses could be reduced by more than 4 orders of magnitude, to order 10^{-9} or better. A major question, however, is whether or not one should bother. The widely accepted assumption of CPT invariance would insure that antiproton and proton masses are equal. Fig. 8 shows the current status of experimental tests of CPT invariance, taken from the Particle Data Group compilation[29] with several updates. Since CPT invariance implies that a particle and antiparticle have the same magnetic moment (with opposite sign), the same inertial mass and the same mean life, the tests are so grouped. The fractional accuracy is plotted, and baryons, mesons and leptons are distinguished. The neutral kaon system provides a test of CPT invariance of striking precision. Equally striking, however, is that only 3 other tests exceed 1 part per million in accuracy, and these involve leptons only. In fact, there is not even a single precision test of CPT invariance with baryons. The widespread faith in CPT invariance is clearly based upon the success of field theories in general and not upon a dearth of precision measurements.

We note here that it is even conceivable that proton and antiproton masses could be different without a violation of CPT invariance. Precisely stated, CPT invariance relates the mass of a proton in a matter universe to an antiproton in an antimatter universe. A long range coupling to baryon number would not affect the kaon system but could shift differently the proton and antiproton masses, given the preponderance of baryons in our apparatus and universe.

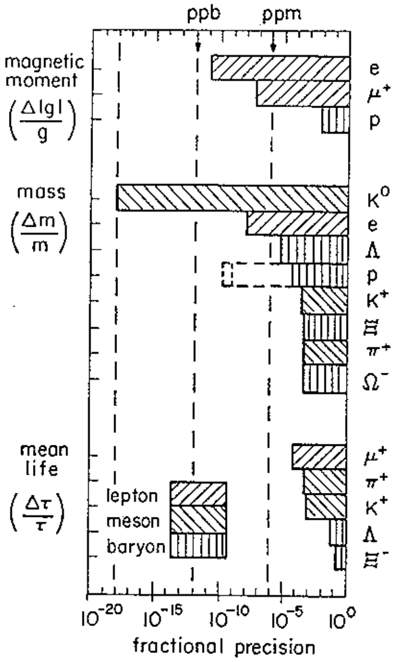

Fig. 8. Fractional accuracy in experimental tests of CPT invariance.

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[29] Particle Data Group, Rev. Mod. Phys. **56**, S1 (1984).

The scarcity of precise tests of CPT invariance makes the case for a precise comparison of proton and antiproton masses seem to be very strong to me, especially since no precise test at all involves baryons. Such a measurement also satisfies several additional criteria.

1. A big improvement in accuracy is involved, somewhere between four and five orders of magnitude.
2. A simple, basic system is involved.
3. The technique used will be convincing if the masses are found to differ.
4. The measurement will involve a reasonable effort.
5. It will be fun.

The last two criteria are more subjective than the others, but important nonetheless.

Since Vernon Hughes is one of my fellow lecturers at this school, I end this discussion by quoting him and his collaborators, from their published account of one of the early measurements of the antiproton mass by the exotic atom method.[25]

> Formalistically, the equivalence of mass and lifetime of particle and antiparticle is a consequence of the CPT theorem, which also predicts that the magnetic moments of particle and antiparticle are equal in magnitude but opposite in sign. It is clearly of interest to make precise measurements of such basic quantities for the antiproton, not only for the intrinsic value, but also for the knowledge it may yield concerning the basic symmetries underlying the matrix of physical thought.

D. First Slowing and Capture of Antiprotons in an Ion Trap

As you well know, antiprotons are created at energies of several GeV. Precision experiments in Penning traps take place at millielectron volts (meV). An experimental difficulty, then, is to reduce the antiprotons kinetic energy by approximately 12 orders of magnitude, as illustrated in Fig. 9. The first slowing, from GeV energies down to MeV energies takes place within LEAR. The unique capabilities of this machine are well known here, so I will not discuss them further.

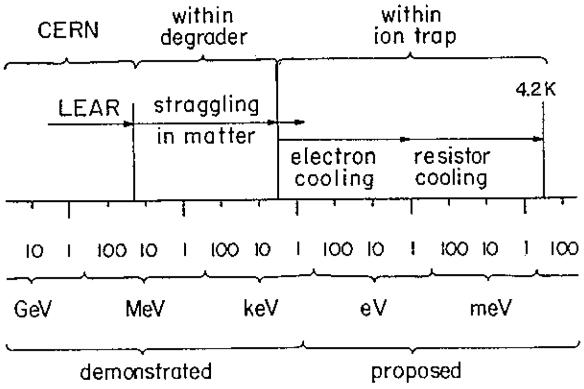

Fig. 9. Antiprotons produced at several GeV energies must be slowed to below a meV for a high precision mass measurement.

I am delighted to report that in the last several months the TRAP Collaboration (PS196) has taken 21.3 MeV antiprotons from LEAR (200 MeV/c) and slowed them down to below 3 keV. At this energy they were caught in the small volume of an ion trap and help up to ten minutes. Members of the TRAP Collaboration are listed in Fig. 10. I should point out that this effort succeeded despite incredible time pressure. The capture of antiprotons, for example, occured during a single 24 hour period.

TRapped AntiProton Collaboration
(TRAP Collaboration)

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S.L. Rolston
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T.A. Trainor

University of Mainz
H. Kalinowsky
J. Haas

Fermi National Accelerator Laboratory
W. Kells

Fig. 10. TRAP collaboration.

The experiments went in two stages. In May, we used a simple time-of-flight apparatus to measure the energy distribution of antiprotons emerging from a thick degrader. Since we have not yet finished our analysis, I present in Fig. 11 only a preliminary result taken on line during the May run. The upper graph shows transmitted antiproton intensity versus thickness of the degrader. As degrader thickness is increased, the number of antiprotons drops as more of them are stopped in the degrader. The degrader thickness at the half intensity point is very close to the proton range which is compiled in standard tables. All energies of transmitted antiprotons are included and most of these antiprotons have energies above 3 keV which is the highest energy we could trap.

The lower curve in Fig. 11 is more crucial. Here the number of antiprotons which emerge from the degrader with low kinetic energies (along the beam axis) between 2 and 8 keV is plotted versus degrader thickness. The low energy flux is clearly peaked at the half intensity point of the upper curve. Approximately 1 in 10^4 of the incident antiprotons emerges from the degrader with below 3 keV. These are the particles available for trapping.

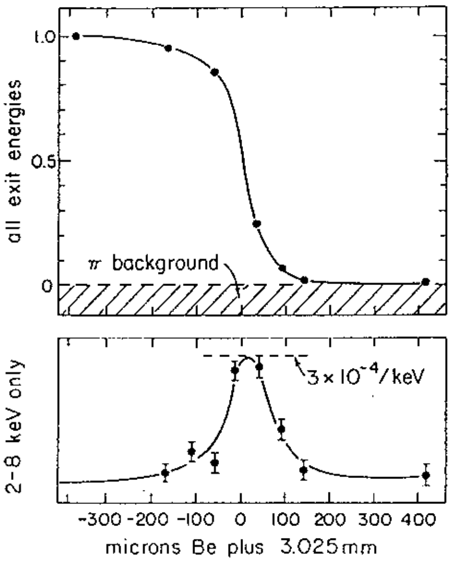

Fig. 11. Transmission of antiprotons through material versus effective thickness of Be.

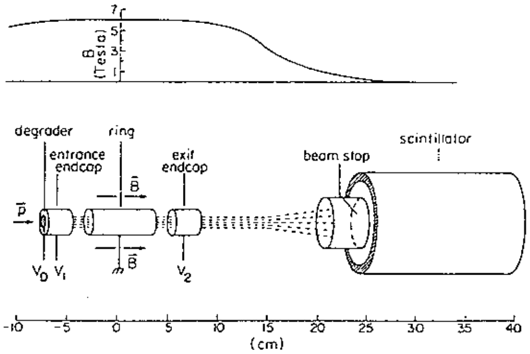

Fig. 12. Ion trap in which first capture of antiprotons took place.

In July we returned to LEAR for a 24 hour attempt to actually catch antiprotons in the small volume of an ion trap. An account of our success is appearing in Physical Review Letters,[30] so I will only briefly summarize. The trap is very simple as is indicated in Fig. 12. The slowest antiprotons leaving the thick degrader are confined in 2 dimensions to field lines of the 6T superconducting magnet (dotted lines in Fig. 12) and are so guided through the series of 3 trap electrodes. As the antiprotons enter the trap, the first ring-shaped trap electrode (the entrance endcap) and the main ring electrode are both grounded. The third cylindrical electrode (exit endcap) is at -3 kV so that negative particles with energy less than 3 keV turn around on their magnetic field lines and head back towards the entrance of the trap. Approximately 300 ns later, before the antiprotons can escape through the entrance, the potential of the entrance endcap is suddenly lowered to -3kV, catching them within the trap. The potential is switched in 15 ns with a kryton circuit developed for this purpose and is applied to the trap electrodes via an unterminated coaxial transmission line.[31] The 3 keV potentials and 15 ns rise times contrast sharply with the several volt potentials and the 100 ns switching times used recently to capture Kr^+ in a few eV well.[19]

After antiprotons are held in the trap between 1 ms and 10 minutes, the potential of the exit endcap is switched from -3 kv to 0 volts in 15 ns, releasing the antiprotons from the trap. The antiprotons leave the trap along respective magnetic field lines and annihilate at a beam stop well beyond the trap. The high energy charged pions which are released are detected in a 1 cm thick cylindrical scintillator outside the vacuum system. A multiscaler started when the potential is switched records the

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[30] G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, W. Kells, Phys. Rev. Lett. 57, 2504 (1986)

[31] X.Fei, R.Davisson and G.Gabrielse, Rev. of Sci. Inst. (in press).

number of detected annihilations over the next $6\mu s$ in time bins of $0.4\mu s$. A second multiscaler records the pion counts over a wider time range with less resolution to monitor backgrounds. This time-of-flight method is similar to but less refined than that used on very low energy electrons and protons ejected from a Penning trap with a 6 volt potential well.[14]

Fig. 13 shows a time-of-flight spectrum for antiprotons kept in the trap for 100s. The spectrum includes 31 distinctly counted annihilations which corresponds to 41 trapped particles when the detector efficiency is included. We carefully checked that these counts are not electronic artifacts. When the high voltage on the exit endcap is switched to release antiprotons from the trap, a single count (occasionally two) is observed in the multichannel scalers. We take this to be time $t = 0$ and always remove a single count from the measured spectra. Otherwise, the background is completely negligible. When the potential of the entrance endcap is switched on just 50 ns before 3 keV antiprotons arrive in the trap, when the magnetic field is off, or when the -3 keV on one of the electrodes is adiabatically turned off and then back on during a 100s trapping time to release trapped antiprotons, no counts are observed.

The potential on the exit endcap is lowered quickly compared to the transit time of particles in the trap in order to maximize the detection efficiency. Even a small number of trapped particles can be observed above possible background rates in the $6\mu s$ window. For trapping times shorter than 100s, however, we actually released so many trapped antiprotons that our detection channel is severely saturated. For a 1 ms trapping time, we conservatively establish that more than 300 antiprotons are trapped out of a burst of 10^8, which corresponds to trapping 3×10^{-6} of the antiprotons incident at 21.3 MeV and 3% of the antiprotons slowed below 3 keV in the degrader. We observe that 5 particles remain in the trap after 10 minutes. This is actually based upon only two trials (since we were reluctant to use up our short time at LEAR holding antiprotons for long times), but both of these trials used a burst of antiprotons from LEAR of comparable intensity to that used for the 41 trapped particles of the 100s spectra in Fig. 2. If a simple exponential decay describes the number of particles trapped between 100 a and 10 minutes, the decay time is 240 seconds. An extrapolation back to the loading time $t = 0$, however, would then indicate that only 62 particles are initially trapped. We clearly observe many more for a trapping time of 1 ms, suggesting that antiprotons are lost more rapidly at earlier times.

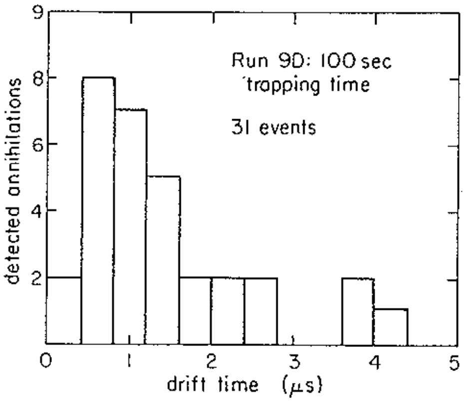

Fig. 13. Time of flight spectra, started when antiprotons were released from the trap.

A key point here is that the rate of cooling and annihilation via collisions with background gas will decrease with decreasing pressure. The background pressure can be made lower by orders of magnitude compared to the present vacuum by cooling a completely sealed vacuum enclosure to 4.2K. We thus expect a very significant increase in achievable trapping times.

E. Cooling Particles Within the Trap

If, as we suspect, we will soon be able to hold antiprotons in a trap for times much longer than 10 minutes, we feel rather confident that we will be able to cool them from approximately 1 keV down to of order meV. When the background pressure is greatly reduced, electron cooling seems to be the most promising method of cooling trapped antiprotons from keV to eV energies. In fact, electrons are probably already confined in the present trap, under the assumption that each antiproton emerging from the degrader liberates several electrons and many of them are trapped. A 1 keV antiproton traveling through a cloud of 1 eV electrons with density of $10^8/cm^3$ loses energy exponentially with a time constant of 1 s or less, which is much shorter than the time antiprotons were held. Although such a calculation of electron cooling rates within a trap was only done recently,[32] and the possibility of spatial separation of trapped electrons and antiprotons must be investigated,[33] such cooling is quite well understood both experimentally and theoretically insofar as cold electron beams have often been used to cool various particle beams traveling along the same axis with the same velocity.[34]

We presently prefer electron cooling as a first step because no resonant frequencies are involved and it thus promises to be the quickest cooling scheme. Once the amplitude of the oscillation along the magnetic field line is sufficiently reduced, the oscillation frequency of this oscillation will become increasingly independent of amplitude. It then should be possible to couple to a resistor such as that used to detect induced currents using a tuned circuit to cancel out the trap capacitance on resonance. The induced current dissipates power in the resistor. This removes energy from the axial oscillation, cooling the axial motion to the temperature of the resistor. Resistor cooling is a well established technique which has been used for many years.

F. Antihydrogen Production

Several lectures at this school are devoted to the production of antihydrogen. The method discussed involves colinear, velocity matched beams of antiprotons and positrons within LEAR. While I would prefer to wait until we have completed a more detailed study which is under way, I think it would be unfortunate if some thoughts about antihydrogen production in traps were not part of this school. If one could make antihydrogen in a particle trap, this would impact LEAR itself very much less than the merged beams approach. Many years ago, we mentioned the possibility of putting positrons and antiprotons into a radio frequency trap at the same time in

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order to make antihydrogen.[35] At that time, there was no promising proposal for getting antiprotons in a trap, but this of course is no longer the case. More recently, we mentioned the possibility which we have been studying for some time, of using a nested pair of Penning traps to simultaneously capture positrons and antiprotons.[36]

To provide a concrete starting estimate, consider a cloud of positrons of volume density n in thermal equilibrium at 4.2 K. For simplicity, we will assume the positrons are each moving with the average speed $\bar{v} = 10^6 cm/sec$. If we now simultaneously fill the same volume with N antiprotons, with energies below 1 ev, the relative velocity between antiprotons and positrons is the positron velocity $\bar{v}$, since antiprotons are much heavier. The antiproton production rate is thus approximately given by

$$R \approx Nn\sigma\bar{v}. \tag{10}$$

The cross section for radiative recombination to any antihydrogen bound state is well known[37] so that

$$\sigma \approx \frac{1}{10}\sigma_B \approx 10^{-17} cm^2 \tag{11}$$

for $\bar{v} = 10^6 cm/sec$, where σ_B is the Bohr cross section. Suppose we take $N = 10^4$ which is larger than we have already achieved by a factor of 10 but looks to be a realistic expectation. We further assume that $n = 10^8$ positrons/cm^3 can be placed in a trap at in thermal equilibrium at 4.2K. Together this gives a production rate

$$R \approx 10/sec. \tag{12}$$

This rate could possibly be made larger by stimulation with a laser as suggested for the merged beams experiment,[38] perhaps by a factor of 10, depending upon how small the interaction region can be made. Our favorite scheme is to stimulate to $n = 3$ or higher, perhaps even with a diode laser. However, the effective rate is actually lower owing to the duty cycle involved in loading a trap with antiprotons from LEAR.

Such low rates might be sufficient to observe antihydrogen for the first time. When antihydrogen is formed in an ion trap, the neutral atoms will no longer be confined and will thus quickly strike the trap electrodes. Resulting annihilations of the positron and antiprotons could be monitored. However, it is very clear that the very low rate will make further experiments with antihydrogen to be very different than experiments with copious amounts of hydrogen, and much more difficult.

For me, the most attractive way around this difficulty would be to capture the antihydrogen in a neutral particle trap such as has been used for neutrons[39] and neutral atoms[40,41] The objective would be to then study the properties of a small number of

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atoms confined in the neutral trap for a long time. To capture an antihydrogen atom directly into a neutral trap would require a neutral trapping well depth of order 4.2 K or 3×10^{-4} eV. This unfortunately is many orders of magnitude deeper than what is being realized. Thus, laser cooling and optical molasses techniques would be required, with Ly α lasers. The technologies which would need to converge in order to permit the study of antihydrogen in a neutral trap is rather imposing, but may be possible. It would also be necessary to minimize the rather strong interactions of the atom and the neutral trap in order cto meaningfully study the properties of antihydrogen.

Since I am speculating in this section, let me make several comments relevant to the discussions about gravity which are part of this school. I find the possibility of measuring the acceleration due to gravity for a antiproton to be very appealing, if it can be done. Another group is presently endeavoring to demonstrate that such a measurement can be done with charged particles.[42] We are investigating a different approach, to see whether such a measurement could possibly be done instead with neutral antihydrogen, in order to reduce the extreme sensitivity to stray charges.

Finally, to avoid the small cross sections involved in radiative capture, it has been proposed to send positronium into a cloud of trapped antiprotons.[43] The cross section is several orders of magnitude larger, but because the positronium can not be confined in the same volume as the antiprotons for a long time, the rate seems to be lower than considered here. There are nonetheless attractive features to this approach and we are studying it further.

G. Acknowledgements

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