PROSPECTS FOR EXPERIMENTS WITH TRAPPED ANTIPROTONS

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(* Presented by G. Gabrielse)

Abstract

For this particular conference, I should like to go on the record as being one of the earliest advocates of a low energy antiproton facility in the United States. In 1981 I presented a colloquium at the University of Chicago about experiments with trapped electrons and then spoke in the particle physics lunch meeting about the desirability of obtaining low energy antiprotons to do similar experiments. I also went out to Fermilab to find out how feasible it was to get low energy antiprotons at Fermilab and to try to generate interest. I was very naive and it seemed to me that the small ring then being used to investigate electron cooling could perhaps be suitably adapted. Alas, this possibility was never taken seriously. However, these discussions caught Kells interest and he eventually came out and worked with me for a year and we initiated the work discussed here.

We are building upon work done over the last decade at the Universities of Mainz and Washington, in which Penning traps were used to confine elementary particles for precision measurements. Based upon the success in confining single electrons, positrons and protons, we are undertaking similar studies with antiprotons. The first objective is a comparison of the antiproton and proton masses. An accuracy of 1 part in 10^9 seems possible based upon demonstrated linewidths with protons, electrons and positrons. This is an improvement of 10^4 over present measurements. This measurement will be the first high precision test of CPT invariance with baryons and will be one of the three highest precision tests of CPT invariance. In preparation for the antiproton experiment (CERN PS 196), we have directly trapped kilovolt protons for the first time and have measured the probability of producing keV protons by degrading 18 MeV protons in a thick beryllium window. We have also demonstrated the feasibility of using cylindrical trap electrodes for storing a cold electron cloud for electron cooling. A new nested Penning trap configuration is proposed here which may prove useful for electron cooling and for possible antihydrogen production.

A. Ratio of Antiproton and Proton Masses: A fundamental quantity and a test of CPT

The antiproton is one of four simple charged particles (along with the electron, positron and proton) which live long enough that its properties can be measured to extremely high precision while it is confined within a Penning trap. We propose here to measure the ratio of the antiproton and proton masses to an accuracy exceeding 1 part in 10^9. This is an improvement over the best existing measurements[1] by a factor of 10^4 in this fundamental ratio. Invariance under CPT would require that the mass, magnetic moment and decay width of a particle and antiparticle be identical, except that the sign of the magnetic moment is reversed. Experimental tests of CPT invariance are now reviewed regularly as part of the compilation of elementary particle data[1] and 17 tests are presently listed with widely varying precisions. Only two have an accuracy near or exceeding the accuracy we propose to attain. The electron and positron magnetic moments are measured to be the

[1] A compilation of particle data is in Rev. Mod. Phys. *56*, S37 (1984).

same to accuracies of 4×10^{-12}. This measurement was made with single electrons and positrons in a Penning trap at the University of Washington.[2] The electron and positron, however, do not participate in strong interactions. In fact, there is only one high precision test of CPT for particles which can interact strongly. This test arises from the famous K_L and K_S mass oscillation which is such a sensitive test of the mass difference of the strong eigenstates, K_0 and $\bar{K}_0$, that the mass eigenvalues of these eigenstates must differ by less than a phenomenal 10^{-19}. While it is not conceivable to achieve comparable sensitivity with the antiproton and proton system, it is not clear just how a CPT violation would affect masses. It is possible that this three-quark baryon system is affected differently than quark-antiquark mesons. An instructive example is CP violation which at present has been observed only in the kaon system. The wide acceptance of CPT invariance is based upon the success of field theories and not upon a large number of precision measurements. An orders of magnitude improvement in the antiproton-proton mass ratio, by a direct measurement, would thus provide an important additional CPT test.

B. Measuring a Mass in a Penning Trap

A Penning trap is a nearly ideal environment for measuring the properties of a charged particle. The confinement times are extremely long (for example, more than ten months for a single electron[3]) and the perturbations are extremely weak. In a Penning trap a charged particle (or particles) is confined radially by a strong magnetic field. In the 6 Tesla field we intend to use, the cyclotron frequency for an antiproton is 90 MHz. Comparing the cyclotron frequency of an antiproton and a proton (or perhaps a H^- ion) in the same magnetic field yields the mass ratio. Actually, it is a comparison of charge to mass ratios, which are then interpreted as a comparison of masses under the assumption that the charges of the particle and antiparticle are equal in magnitude but opposite in sign, just as has been measured so accurately for the electron and proton. An electrostatic quadrupole potential is superimposed to keep the charged particle from drifting out of the trap along a magnetic field line. This addition adds an axial oscillation and a magnetron motion to the cyclotron motion. The cyclotron motion is basically unchanged, except that the cyclotron frequency is slightly reduced. The axial oscillation is parallel to the magnetic field at a frequency which is lower than the cyclotron frequency, but is still in the MHz range. For a pure quadrupole potential this motion is harmonic. The magnetron motion is circular and, like the cyclotron motion, is in a plane perpendicular to the magnetic field. The magnetron frequency is much lower than the other frequencies, typically in the kHz range.

Precision measurements on electrons, positrons and protons in Penning traps are well enough known and documented in the literature that we need not go into further detail about these established techniques. Instead we mention the state of the art in such precision measurements. At the University of Mainz, small numbers of electrons and protons were

[2] The most recent discussion of this work is by R.S. Van Dyck, Jr. and will appear in the Proceedings of ICAP IX, edited by E.N. Fortson and R.S. Van Dyck, Jr.

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

ejected from a Penning trap into a channel plate detector.[4] Precisions of 5×10^{-7} and 2×10^{-7} were obtained in the electron and proton cyclotron frequencies, respectively. Interrogation of single particles by resonance techniques is a highly refined, local specialty at the University of Washington which has yet to be duplicated. Single electrons and positrons have been trapped and their masses and magnetic moments measured to the accuracy of 4×10^{-12} mentioned above. More recently, the best signal to noise ratio ever observed with a single particle was obtained as a consequence of special relativity with a trapped electron whose kinetic energy was as low as 10 milli-eV.[3] Also the first observation of the inhibition of the spontaneous decay of a radiating system by a surrounding microwave cavity was observed.[5] The electron and positron techniques have been adapted to measure the ratio of proton to electron masses[6] and a single trapped proton has recently been detected for the first time after many years of effort. The most accurate value of the proton to electron mass ratio (an accuracy of 3×10^{-8}) was obtained with a small number (≤ 5) of protons. While the mass ratio measurement has not yet been repeated with a single trapped proton, cyclotron linewidths narrower than 1 part in 10^{-9} have been observed. Precision measurements with small numbers of elementary particles have only been carried out successfully at these two institutions.

Along with the experimental progress, theoretical progress has also been made in understanding particle trapping in recent years. Of great importance for precision mass spectroscopy is the derivation of a simple prescription for the cyclotron frequency for a particle in a magnetic field in terms of the three measurable eigenfrequencies of a Penning trap.[7] The beauty of this prescription is that it is insensitive to the major imperfections in a laboratory Penning trap and thus enhances the prospects for precision spectroscopy in an imperfect Penning trap. Also, the electrostatics of Penning traps is now much better understood, and a new orthogonalized compensated electrode design has been proposed which should greatly simplify the tuning out of the leading imperfections of the electrostatic quadrupole field.[8] The displacement of the center of the harmonic axial oscillation (parallel to the magnetic field) is better understood along with the detection of this motion.[9] A review of theoretical progress is now nearly finished and will appear in the Reviews of Modern Physics.[10] The point here is that once antiprotons are trapped and cooled (Sections C and D), the mass measurement will be very similar to the measurements described above and will profit from the theoretical progress described above. This does not mean that a precision mass measurement will be quick or easy in any sense. It is absolutely clear from the electron, positron, and proton experiments that a precision measurement requires the fewest possible trapped particles, preferably only one. Even without the additional apparatus which must be present to trap and cool antiprotons, a great deal of painstaking

[4] G. Gartner and E. Klempt, Z. Physik *287A*, 1 (1978); G. Graff, H. Kalinowsky and J. Traut, Z. Physik *297*, 35 (1980).

[5] G. Gabrielse and H. Dehmelt, Phys. Rev. Lett. *55*, 67 (1985).

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

[7] L.S. Brown and G. Gabrielse, Rapid Comm. of Phys. Rev. A *25*, 2423 (1982).

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

[9] G. Gabrielse, Phys. Rev. A *29*, 462 (1984).

[10] L.S. Brown and G. Gabrielse, to be published.

tuning of the apparatus and the detection electronics is required to interrogate a single elementary particle.

C. Trapping Antiprotons

The one major difference with antiprotons in a trap, compared to protons, is that the vacuum requirements are much more stringent, because a collision with a background gas atom can result in a "spiraling in" trajectory, an Auger process and finally an annihilation.[12] We estimate that a vacuum of 10^{-14} Torr is required with a room temperature pump to achieve less than 1 annihilation per day. This vacuum requirement is more stringent than that faced in the LEAR ring itself because the antiprotons in a trap have much lower kinetic energies and the annihilation cross sections are therefore much higher. A somewhat lower pressure is actually desired so that the antiprotons can be trapped indefinitely. The only way to obtain such a low pressure is to submerge a sealed containment vessel in liquid helium.[13] This is the way that we presently attain vacuum in the monoparticle experiments at the University of Washington and many technological improvement have been made in the construction of traps in such vessels in recent years.[14] Antiprotons would enter the vessel through a thin metal window as we shall discuss presently.[15] This possibility was also mentioned but not developed in the most recent proposal by an Italian collaboration.[16]

A new technique is required to trap the antiprotons. The electrons and protons used in previous experiments were produced within the well of the Penning trap by ionizing or scattering from a background gas atom. To load particles which enter from outside the trap is more difficult because particles which have enough energy to enter the Penning trap will also have enough energy to escape the trap unless some energy is quickly removed from the particle as it passes through the trap. Positrons were externally injected and subsequently cooled via an interaction with an external damping resistor.[17] This approach is not possible with externally injected antiprotons or protons, however, because the damping rates go inversely as the mass of the trapped particle and are thus much too small.

The alternative is to build a quadrupole potential up around the particle as it passes through the trap electrodes.[15,16] Careful numerical studies of axial loading show that it is necessary to apply a quadrupole potential quickly with respect to the period of the axial oscillation (parallel to the magnetic field) which results from this potential. For

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[12] L. Bracci, G. Fiorentini and O. Pitzurra, Phys. Lett. *85B*, 280 (1979).

[13] W. Thompson and S. Hanrahan, J. Vac. Sci. Tech. *14*. 643 (1977).

[14] G. Gabrielse and H. Dehmelt, in *Precision Measurements and Fundamental Constants II*, B.N. Taylor and W.D. Phillips, Eds., Natl. Bur. Stand. (U.S.), Spec. Publ. 617 (1984).

[15] W. Kells, G. Gabrielse and K. Helmerson, Fermilab-Conf.-84/68-E, originally presented at the ICAP IX meeting in Seattle, WA in August, 1984.

[16] N. Beverini, L. Bracci, V. Lagomarsino, G. Manuzio. R. Parodi and G. Torelli, CERN/PSCC 83-14, given to us at ICAP IX.

[17] P.B. Schwinberg, R.S. Van Dyck, Jr. and H.G. Dehmelt, Phys. Lett. *81A*, 119 (1981).

our estimates here, we shall take the axial oscillation frequency to be $\nu_z = 20$ MHz, which is approximately the largest possible axial frequency which can be obtained in a 6 Tesla magnetic field while still retaining an adequate radial restoring force. This is the largest field which can be obtained in a commercial superconducting solenoid without compromising the stability and homogeneity required for a precision mass measurement. We thus must apply the trapping potential with a time constant of approximately 5 ns. (This time could be eased somewhat from this worse case estimate by making the trap larger and thereby reducing ν_z but space constraints in the bore of a superconducting magnet will preclude large changes here.) Current high voltage switching technology will certainly allow the application of a 5 kV potential on this time scale. With this trapping potential, antiprotons with energies less than approximately 2.5 keV can be trapped. The need to apply this potential within a helium bath will necessitate the use of a low heat loss transmission line and will constitute an interesting experimental challenge. The axial loading scheme will be tested with electrons and protons as outlined in Sec. F.

As magnificent as the LEAR decelerator is, the 5 MeV kinetic energies obtained are still many orders of magnitude larger than the 2×10^{-4} eV desired for the precision measurement. We propose to use the simplest possible method to go from 5 MeV to less than 2.5 keV. We will bring the 5 Mev antiprotons nearly to rest in the same window used to preserve our ultra high vacuum.[15]. An aluminum or beryllium window which is approximately 0.2 mm thick, for example, could be used to "range out" antiprotons. Straggling within the window would spread out a 5 MeV beam (even with no initial energy spread) to a width $\Delta E \approx \pm 250$ keV in the energies of the slow antiprotons leaving the window. Since only energies below 2.5 keV could possibly be trapped with a 5 kV potential, this represents an immediate loss of 99% of the antiprotons. For comparison, in a perfect decelerator (i.e. limited by the Liouville theorem), the energy spread in the decelerated beam would be equal to the energy spread of beam fast-extracted from LEAR. This spread is expected[18] to be only about 10 times better with $\Delta E \approx \pm 20$ keV. Without much sacrifice in performance, therefore, a degrader has the important advantage that it should be possible to use the LEAR facility without requiring the construction of additional (and substantial) decelerator and cooling stages. In addition, the stringent vacuum requirements mentioned earlier are satisfied simply and naturally with a degrader since the vacuum vessel surrounding the trap can be completely enclosed and immersed in liquid helium.

D. Degrader Tests with a Time-of-Flight Spectrometer

We intend to initially slow antiprotons from LEAR energies of 5 to 20 MeV, down to keV energies by sending the beam through a thick degrader. Since degrading to such low energies has not been well studied before, we prepared the simple time of flight spectrometer shown in Fig. 1. The high energy particles pass first through a thin plastic scintillator (127

[18] This has been studied, for example by H. Herr for extraction to ELENA in *Physics at LEAR with Low Energy Cooled Antiprotons*, p. 634, U. Gastaldi and R. Klapisch, Eds. (Plenum, 1984).

microns in the most recent version) which provides a start signal. The protons continue through a thick degrader, with thickness chosen to be the range of the incident particles, and eventually arrive at the channel plate detector. An exterior scintillator (not shown in the figure) will be added t LEAR to detect pions from proton-antiproton annihilation.

We are scheduled to use this spectrometer at LEAR in several weeks to measure the distribution of low energy antiprotons coming from the degrader. As an initial test, we used incident protons from the tandem accelerator at the Nuclear Physics Laboratory at the University of Washington, instead of antiprotons. A typical proton, time-of-flight spectrum is shown in Fig. 2. The time on the horizontal scale increases from right to left because the channel plate was actually used to start a time-to-amplitude conversion while a delayed pulse from the thin plastic scintillator was used a a stop. This arrangement reduced the accidental background by taking advantage of the low dark count rate in the channel plate. We regularly see on the order of 10^{-5} to 10^{-4} in a 1 keV slice at an exit energy near 1 keV. This is consistent with our earliest estimates and with the recent calculation we have done with the TRIM code of Ziegler, Biersack and Littmark.

E. First Direct Trapping of keV protons

We intend to directly trap the antiprotons which exit from the degrader with energies less than several keV. The beam emittance after the thick degrader will be very poor. The large momentum components perpendicular to the incident beam direction thus preclude decelerating the degraded beam to energies of a several eV, where the particles can be more easily trapped.[20] While the magnetic field will provide some radial confinement, we must still trap the keV particles directly, without slowing them, by applying kilovolt potentials to the trapping electrodes after the particles have entered the trap. The kilovolt potentials must be applied quickly compared to the transit time of the particles through the trap. We have been able to apply 4 kV potentials in approximately 10 ns. using krytons.

To investigate the trapping process, we sent a 1 keV proton beam from an ion source through a very crude trap. A Helmholtz coil provided a 2 kG. field and cylindrical trap electrodes were made of conventional 2 3/4 inch conflats and vacuum pipes. Protons were trapped from a pulse with instantaneous intensity of approximately 4 nA sent through the trap by suddenly raising the potential of the upstream electrode. We held the protons for several milliseconds, and then quickly lowered the kV potential of the down beam electrode so that trapped protons could escape from the trap towards the channel plate detector. A multiscaler, started when the potential was lowered accumulated a time-of-flight spectrum of pulses from the channel plate. As shown in Fig. 3, the 1 keV protons trapped from the beam arrive at the detector first and make a distinct peak. Soon after, a low energy proton background begins arriving, followed by heavier background ions nc shown in the figure. The background protons and heavier ions are produced when beam protons ionize background gas ions within the trap.

The time of flight spectrum shown is for a single catch of protons from the beam. Approximately 10^2 protons were trapped. The incident beam of 4 nA means that approximately 10^4 protons were within the trap so that approximately 1% of the available

[20] J. Kluge, et. al., to be published.

particles were trapped. The low trapping efficiency is due in large part to the low magnetic field and to the large spatial spread in the incident proton beam. This could be improved. The initial demonstration trap is much more crude than we will use at LEAR where we will also use a magnetic field which is 24 times bigger.

F. Axial Cooling Within the Trap

A second new technique to be developed is axial cooling of large amplitude axial oscillations (parallel to the beam axis and the magnetic field). The trapped antiprotons will have energies in this axial oscillation which range from 0 to 2.5 keV. To do a precision mass measurement, however, it is necessary to cool this motion to the ambient temperature of 4.2 K. It is difficult to damp this motion with an external resistor (as we do routinely with electrons and positrons at the University of Washington) because the time constant for such damping under the most ideal circumstances is on the order of tens of seconds. An additional difficulty is that the external resistor only damps the axial oscillation when the trap capacitance in parallel with the resistor is tuned out with a parallel inductor. The resonant frequency of this tuned circuit must coincide with the frequency of the axial oscillation and the Q of the circuit is necessarily as high as possible in order to obtain the largest possible resistance and hence the most rapid axial damping. The difficulty arises because of the high Q and the large oscillation amplitudes of the uncooled antiprotons, many of which are oscillating from endcap electrode to endcap electrode. Even with the best possible trap construction and the most careful prior tuning out of electrostatic anharmonicities, the large amplitude oscillations will still be necessarily anharmonic. The axial oscillation frequency will thus depend dramatically upon oscillation amplitude and most of the antiprotons will have an axial oscillation frequency which does not coincide with the resonant frequency of the damping circuit so they will not be cooled efficiently.

As an alternative, we have proposed[15] instead to use an electron buffer gas, trapped in the center of the same trap and cooled to 4.2 K via coupling to an external circuit (as we now do routinely). Antiprotons oscillating through this electron buffer gas will scatter from the cold electrons and transfer energy to them and thus to their resistor damping circuit. This is a near textbook case of electron cooling, though rather different from the electron cooling of high energy beams which has been demonstrated at high energy accelerator facilities. We have calculated a damping time constant of 5 seconds.[15] This process is not resonant and hence the rate is not affected by anharmonicities. A difficulty with the electron buffer gas cooling is that it is difficult to test with protons. It would be necessary to load positrons for a buffer gas. While this is possible, is a rather substantial additional complication.

To verify that antiprotons have been trapped before axial cooling is attempted, we thus intend to initially surround our trap with scintillator to detect the pions produced when antiprotons annihilate. Detection of one annihilation should be possible with high probability. We will also attempt to detect the cyclotron motion with a split ring and another resistor damping circuit such as is used in the proton experiment.[21] The cyclotron

[21] R.S. Van Dyck, P.B. Schwinberg and S.H. Bailey, Proceedings of the Sixth Interna-

frequency is much less effected by anharmonic shifts in the axial frequency and from 20 to 100 particles could be so detected.

G. Demonstration of Cylindrical Electrodes

A Penning trap involves a strong magnetic field for radial binding and an electrostatic potential to provide binding along the axis of the magnetic field. For precise experiments, a pure quadrupole potential is desired so that the oscillation along the magnetic field direction is as harmonic as possible. To this end, trap electrodes for such experiments have typically been machined along the hyperbolic equipotentials of the desired quadrupole potential.

For a variety of reasons, we have been studying the possibility of producing the quadrupole potential using cylindrical rings and flat endplates as proposed by Gabrielse and MacKintosh.[22] In tests with electrons,[23] the cylindrical trap represented in Fig. 1, performed much as hoped. Adjustment of the potential of the compensation electrodes (small rings located between the main ring and the flat endplates) was characterized by a quality factor[8] which is approximately 5 times better than for a typical trap with hyperbolic electrodes that symmetrically approach an asymptote.

The cylindrical trap has been tested for only a relatively short time. Nonetheless, an axial linewidth of 5 ppm has already been observed with a small cloud of electrons. This axial linewidth is already narrow enough for all but the most precise one particle experiments at the University of Washington. Electron clouds of various sizes are readily cooled down to near 4.2 K and are already suitable for the electron cooling of trapped antiprotons which we have proposed. Antiprotons of up to several keV in energy, which oscillate through a cooled cloud of electrons, would transfer kinetic energy to the electron cloud.

I. Nested Penning Traps

To optimize the loading and electron cooling rates in a trap, a year ago we began calculating the properties of a nested Penning trap[24] as indicated in Fig. 4a. The center of the trap is the cylindrical trap of the sort already demonstrated with electrons as discussed in the last section. In the most simple extension, smaller diameter tubes (b,e) are inserted into the endplates and form the ring of an outer trap. Additional rings (a,f) at the end of these tubes close off the trap. The potential wells are shown in the solid lines of Fig 4b. The electrons for electron cooling would reside in the very pure central quadrupole well. The antiprotons would be initially trapped in the cruder potential of the long outer

tional Conference on Atomic Masses (AMCO-VI), J.A. Nolen, Jr. and W. Benenson, eds., Plenum, New York, 1980, p. 173.

[22] G. Gabrielse and F.C. MacKintosh, Int'l. J. of Mass Spec. and Ion Proc. 57, 1 (1984).

[23] G. Gabrielse and K. Helmerson, unpublished

[24] G. Gabrielse and L. Haarsma, to be published.

well. As electron cooling proceeds, the antiprotons would eventually relax into the inner well. For some applications, it may be desirable to improve the potential of the outer trap by dividing the long tube electrodes (b,e) into a series of isolated ring with potentials on each adjusted to make the potential in the outer trap to be a better approximation to a quadrupole.

J. Nested Traps and Antihydrogen

It may be that the nested pair of Penning traps could also be used to produce small amounts of antihydrogen as well. In this application, the potential on the center rings would be reversed so that positrons rather than electrons would be trapped in the center. A relatively large number of positrons could be loaded into the central well under the assumption that large numbers of positrons will be be easier to obtain. The positrons could come from one of the intense 1 eV sources made by sending high energy positron pulses into a thermalizing degrader. The positron cloud could do the "electron cooling" of the antiprotons trapped in the outer well and would be available for "recombination" with the antiprotons to make antihydrogen.

The central positron well is a hill for antiprotons (dashed line in Fig. 4) and will thus slow down the antiprotons when they enter this region. This slowing could be used to considerable advantage since the cross sections for antihydrogen production increases with decreasing antiproton velocity.

The difficulty with antihydrogen production is that the probability for antihydrogen production is very low. To conserve energy and momentum, a free positron and a free antiproton must radiate a photon when combining to form antihydrogen. The collision interaction time is typically much shorter than the radiative decay time of a hydrogen atom and the recombination probability is thus severely suppressed. The very low energies potentially obtainable in a Penning trap compensates to some extent. To get an idea of the rates involved, consider a positron cloud in thermal equilibrium at 4.2 K. Consider antiprotons traveling through this cloud with lower velocities (ie. protons with energies less than 1 eV). The radiative recombination cross section is[25]

$$\sigma \approx 0.1\sigma_B$$

where σ_B is the geometrical cross section πa_B^2 which corresponds to the Bohr radius a_B. For a conceivable 10^8 positrons in a trap and 10^4 antiprotons passing through the positron cloud, this yields a relatively low recombination rate on the order of 100 Hz. This basic rate could be probably be enhanced by resonant excitation with a laser.[26] In fact, the basic rate is low enough that all possible enhancement tricks would probably be required.

[25] See Bethe and Salpeter, *Quantum Mechanics of One and Two Electron Atoms* (Springer, Berlin 1957).

[26] R. Neumann, H. Poth, A. Winnacker, and A. Wolf, Z. Phys. *313*, 253 (1983).

Finally, a radiofrequency trap might be a good environment for production of antihydrogen as we mentioned many years ago.[27] As is well known, a radiofrequency trap contains particles of either sign.

K. Other Experimental Possibilities

The precision mass measurement is an important and fundamental measurement which is challenging, difficult and will take some time to complete. This measurement is clearly the goal of the first experiments. At the same time, however, the experience gained during the mass measurement will likely make it possible to develop a source of cold antiprotons, in thermal equilibrium in a Penning trap at 4 K. The prospect of 10^6 to 10^9 cold antiprotons is very exciting in so far as it raises the possibility of very clean protonium and baryonium studies. It is possible to contemplate trapping antiprotons and positrons in the same radiofrequency trap, for example. Also, antiprotons could be ejected from a trap and aimed at a variety of targets to study interactions at extremely low energies. As we proposed six years ago,[27] such a source could easily be made portable and moved to an appropriate laboratory to be used in antiproton experiments.

What seems clear is that the new techniques for applying potentials rapidly and then cooling within the trap will be required for any measurements with lowest energy antiprotons. In the process of loading antiprotons for the mass measurement, the efficiency of the axial trapping will undoubtedly be improved, as well. It will probably be easier to transfer antiprotons from one trap to another than to so transfer electrons and positron and this latter transfer has already been demonstrated.[28] Nonetheless, practice with this transfer will no doubt improve the efficiency. Also, the required detectors to determine the number of particles in the collection trap, for example, will be developed. The point to be made here is that the pursuit of the mass measurement, using a degrader to decelerate the antiprotons and make possible the ultra high vacuum, is a natural way to get the experience with axial trapping and cooling which will be required to develop a cold antiproton source. Eventually it might be desirable (and we would be interested) to use a post -decelerator after LEAR instead of a degrader to obtain the maximum number of trapped antiprotons. While this is possible, there will be serious additional complications which can be avoided with the result that the initial experiments will be much more manageable.

L. Acknowledgements

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[27] H. Dehmelt, R.S. Van Dyck, Jr., P. Schwinberg and G. Gabrielse, Bull. Am. Phys. Soc. *24*, 757 (1979).

[28] P.B. Schwinberg, R.S. Van Dyck, Jr. and H. Dehmelt, Phys. Rev. Lett. *47*, 1679 (1981).

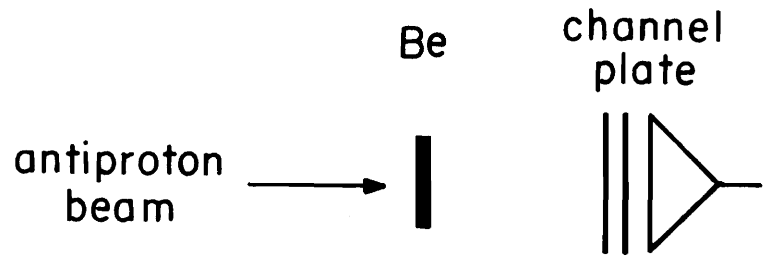


Fig. 1

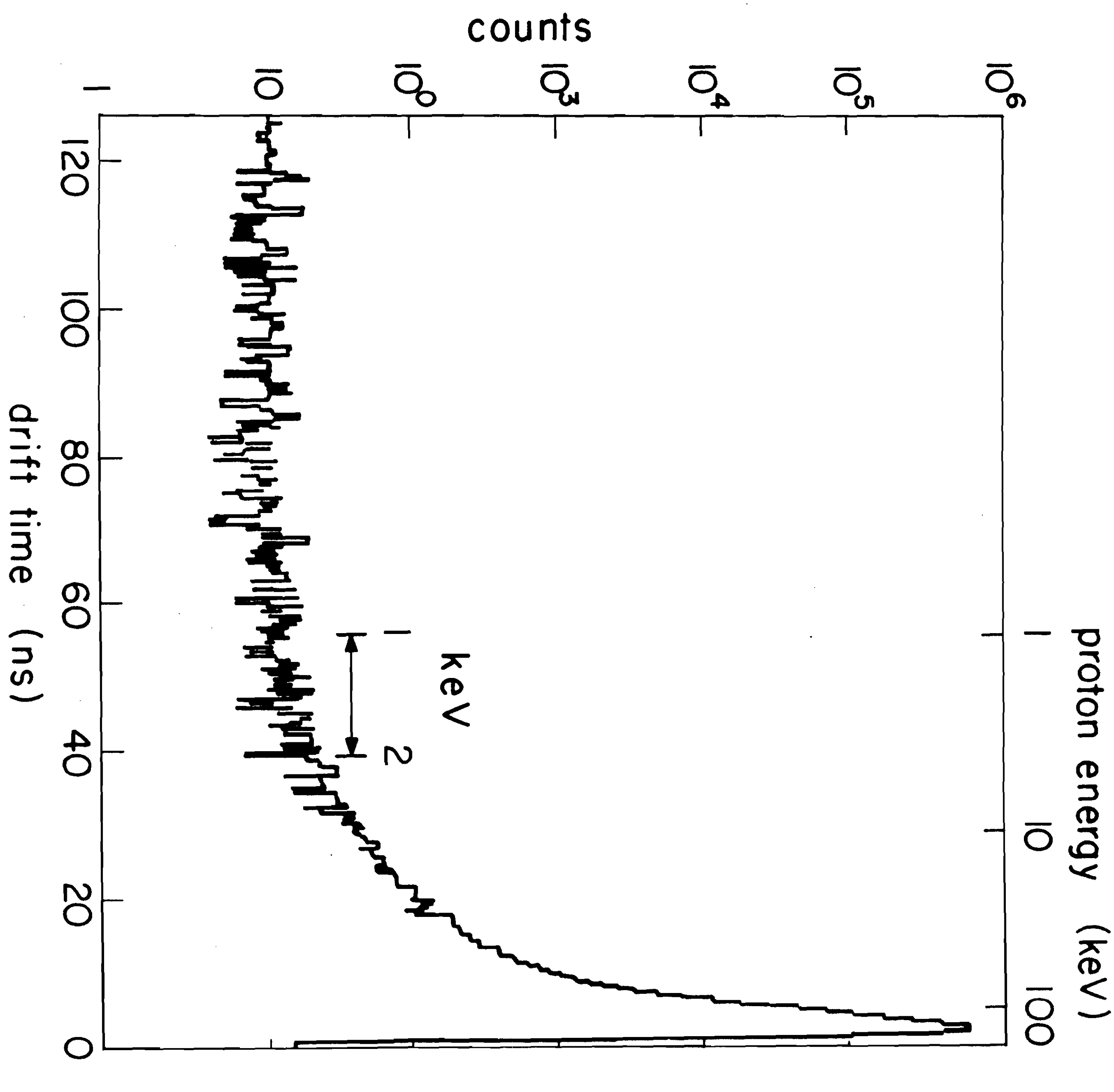


Fig. 2

First Trapping of High Energy Particles

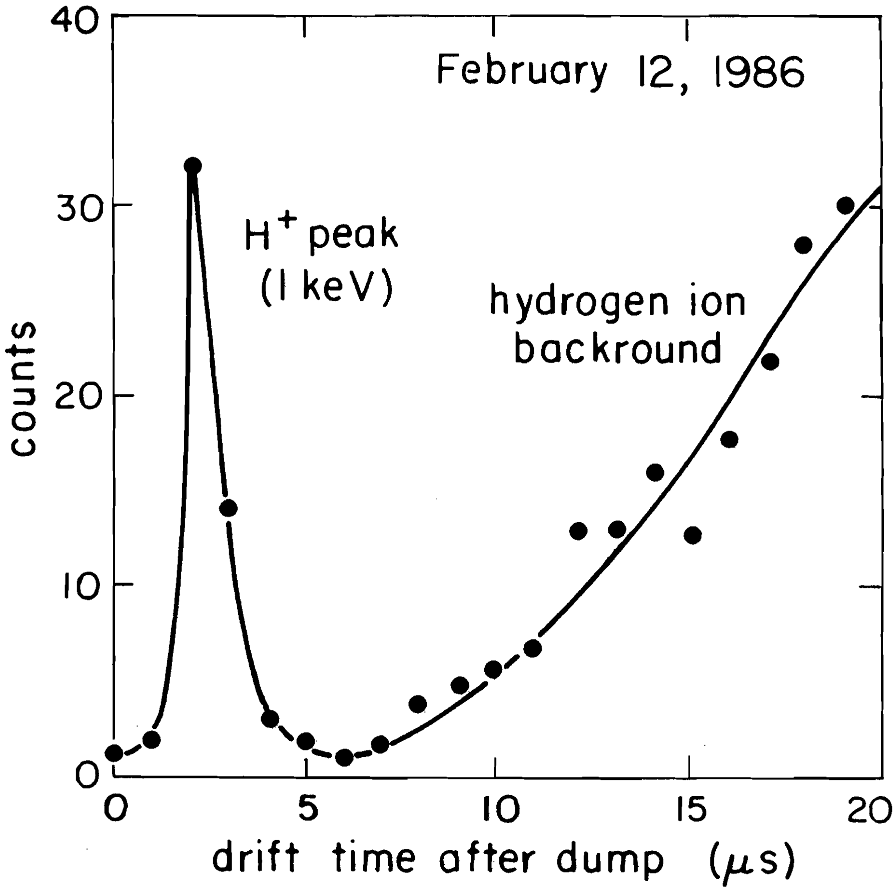
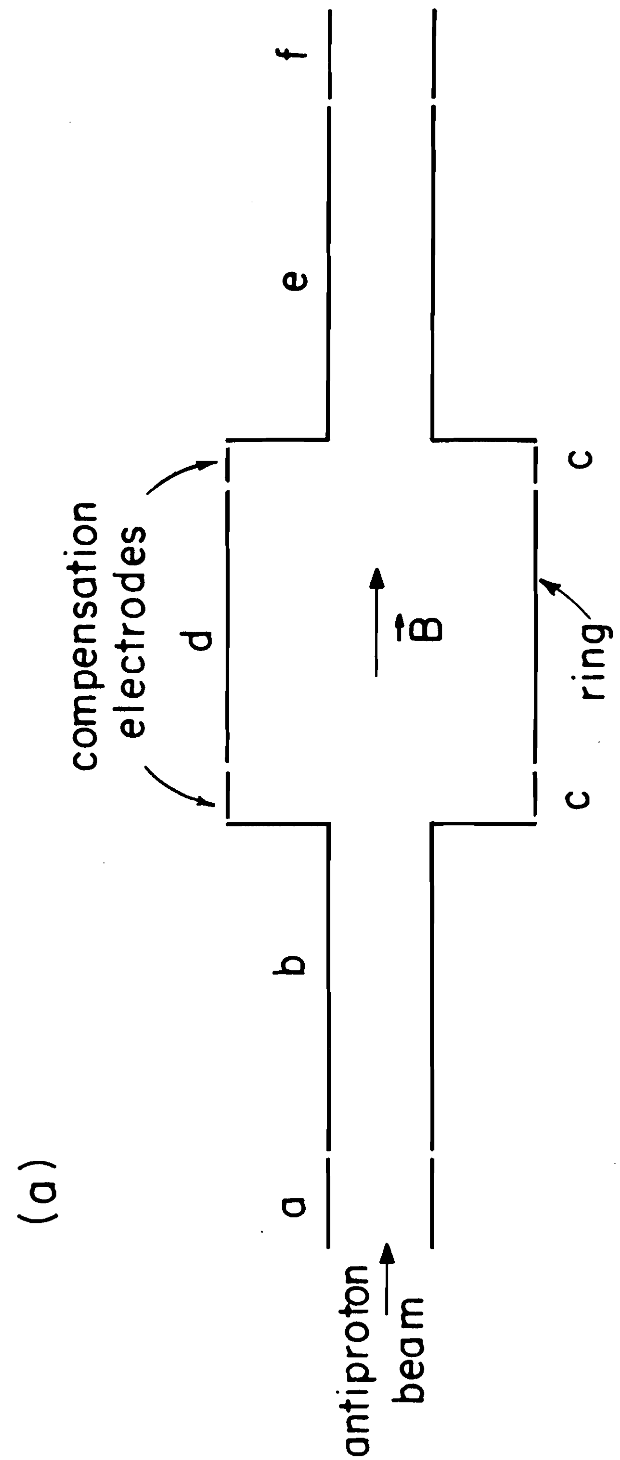


Fig. 3



Fis. 4a

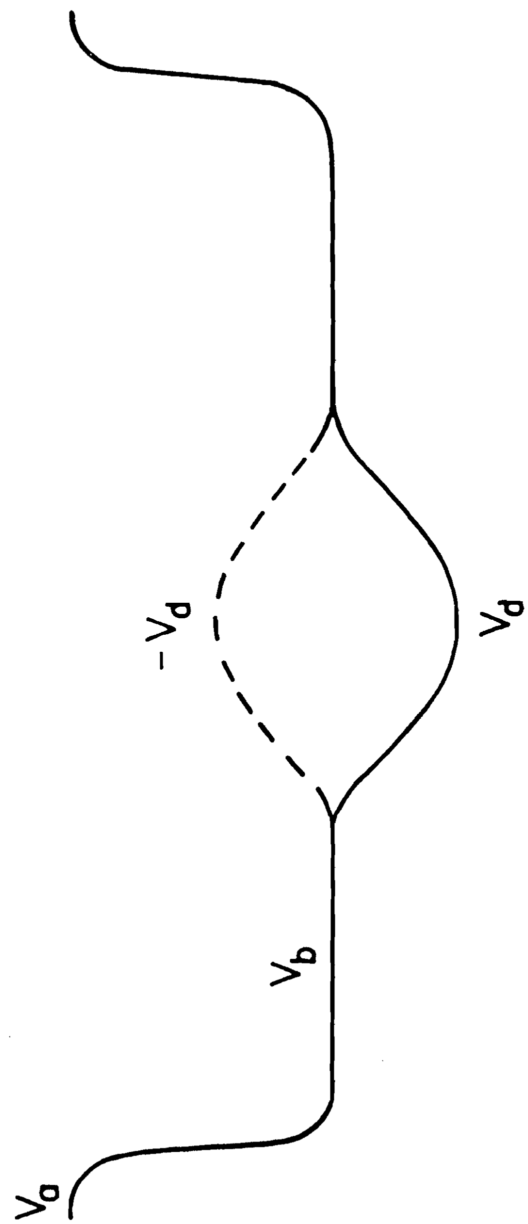


Fig. 4b