PROGRESS REPORT BY THE TRAP COLLABORATION (PS196)

(13 February, 1989)

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Summary

CM-P00044110

Two and one half years ago the TRAP Collaboration captured and briefly stored antiprotons in an ion trap, at energies lower than what is stored at 5.9 MeV in LEAR by more than a factor of 1000. In two and one half months last fall, we made substantial progress. Out of a single pulse of antiprotons from LEAR, we can capture and store more than 60,000 antiprotons in a Penning trap, with a storage lifetime exceeding 50 hours. This represents more than a 200-fold increase in the number of trapped antiprotons and more than a 700-fold increase in storage time. The trapped antiprotons initially range in energy between 0 and 3 keV, and can be stored for days without losing appreciable energy. Under reproducible conditions, however, of order 20,000 antiprotons were cooled below 1 eV, within approximately 20 seconds. This dramatic cooling of the energy distribution (by more than a factor of 1000) may be due to collisions with trapped electrons, but this has not yet been proven experimentally.

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I. Goals and Progress

A. Goals

The goal of the TRAP Collaboration (PS196) is to measure the inertial mass of the antiproton, relative to the proton, to an accuracy of 1 part in 10^9 . This would be an improvement of 50,000 over the present accuracy of 5 parts in 10^5 . It would be one of only a few precise tests of CPT invariance of any kind, and would be the first precise test of CPT invariance with baryons. An excerpt from an Erice Lecture several years ago, in Sec. III, summarizes the status of antiproton inertial mass measurements and of tests of CPT invariance.

B. Two Demonstration Experiments in 1986

In two demonstration experiments in 1986, we demonstrated that

1. Antiprotons could be slowed from 21 MeV (ie. 200 MeV/c) to below 3 keV in sufficient numbers to allow their capture in a Penning trap. The antiprotons were slowed via collisions with bound electrons as they passed through a degrader window. There were some questions about slowing to such a low energy, because degraders had not previously been so employed.
2. The slowed antiprotons could be trapped in a simple Penning trap. We observed 300 antiprotons 1 ms after capture. Due to the saturation of the detector electronics, this was a lower limit. After 10 minutes, 5 antiprotons remained.

Both of these demonstration experiments were done in 24 hour allocations of beam time, separated by more than a month. Despite extensive preparation with protons, we were very lucky that these experiments succeeded. Much credit is due to the LEAR staff, since they were able to deliver intense pulses of antiprotons to us in a completely new mode of operation for LEAR, within the 24 hour window. Our brief report on these experiments¹ is in Sec. IV. An account of these CERN experiments was given in approximately 30 colloquia and invited lectures and was widely reported in the scientific press.

C. While the Antiproton Accumulator Was Improved

While LEAR was out of operation and the Antiproton Accumulator was being improved, we built a completely new apparatus. (Many of us also moved to be closer to CERN). The experience gained in the demonstration experiments, though very brief, was invaluable in helping us design an apparatus which could effectively interface with LEAR. A number of new problems had to be solved.

1. An open access Penning trap was developed.² This trap is composed of a series of ring electrodes and allows the large access required to get the antiprotons into the trap. The rings are arranged so that, despite the large opening into the trap, an electric quadrupole potential is produced in one section of the trap which is of sufficient quality that trapped particles can be observed using nondestructive radiofrequency techniques. The trap was also designed so that a preliminary mass measurement of a precision exceeding 1 part in 10^6 could be carried out within it. Precise mass spectroscopy measurements within a trap have previously been done within Penning traps with hyperbolic electrodes, which allow very little access for the antiprotons.
2. Mass measurements were made in the open access trap with protons and He^{++} . A precision of approximately 10^{-7} was obtained.
3. A "self-shielding, superconducting solenoid" was developed to help us do precise mass spectroscopy in the LEAR hall.³ The problem is that we are located near the magnets of the CERN PS which are energized every few seconds. We observe 35 mG fluctuations at the location of our experiment. A fluctuation of 35 mG superimposed upon our 60 kG field, would make it difficult to do mass spectroscopy with an accuracy exceeding 1 part in 10^6 . Fortunately, the new solenoid system passively cancels these fluctuation by more than a factor of 100. We will probably need to add more shielding before attaining the ultimate precision we seek, but initially we can proceed without requiring a further solution.
4. A position sensitive, parallel plate avalanche detector (PPAC) was developed and tested with protons. (It has more recently performed very well with antiprotons as well.) The PPAC has essentially

¹ G. Gabrielse, X. Fei, K. Helmersen, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas and W. Kells, Phys. Rev. Lett. 57, 2504 (1986).

² G. Gabrielse, L. Haarsma and S.L. Rolston, Intl. J. of Mass Spect. and Ion Proc. (in press).

³ G. Gabrielse and J. Tan, J. Appl. Phys. 63, 5143 (1988).

unit efficiency for a single 5.9 MeV antiproton passing through, a spatial resolution of 2.5 mm and a timing resolution better than 1 ns. In addition, a PPAC is so thin (equivalent to 11 μm of aluminum) that only 320 keV of energy are lost in the pair of PPACs we use (1 for each transverse direction) in the 105 MeV/c beam. The beam can be easily steered and focussed using this detector and we are able to see time structure in the fast pulses sent to us from LEAR. Such PPAC detectors may be useful as next generation trigger detectors for all of the big experiments at LEAR, making it easier for them to actualize the benefits of operation at 105 MeV/c.

D. Dedicated Beam Line at LEAR – Operation at 105 MeV/c Becomes Fixed

A new beam line, designed for our experiments, was completed in August 1988. The beam line was cleverly designed by the LEAR staff to have a very small dispersion, despite a 90 degree bend to direct the beam in through the bottom of our superconducting solenoid. The beam line was located close to LEAR and the beam goes through no splitters in order to make it possible to switch rapidly back and forth between our experiment and others. At the time the design was being finalized, it appeared that the OBELIX, the Crystal Barrel and the CP violation experiment would be operating at 105 MeV/c in order to profit from a better stop distribution. Based upon this perception (which very unfortunately turned out to be mistaken), it was agreed that our beamline would be able to bend a 105 MeV/c beam but not a 200 MeV/c beam. It was difficult (and more expensive) to arrange bending magnets able to handle 200 MeV/c. This caused us some concern because our demonstration experiments had been done at 200 MeV/c. The connection between LEAR and our experiment became more difficult. For example, thinner vacuum windows were required. Eventually, we developed the technique for producing the thinner vacuum windows and provided some of them to LEAR for use with other experiments since they were not available commercially. Despite the added difficulties, there was hope that operation at 105 MeV/c would give us a higher trapping efficiency and this turned out to be true.

E. Proton Test at LEAR

The ACOL delay meant that all our beam time in 1988 would be concentrated in the fall. We wished to do a proton test at LEAR, before antiprotons were available, to give ourselves some time to react to unexpected problems which might arise in the interface to LEAR. This was especially important because our demonstration experiments had been carried out at 200 MeV/c and because some of our apparatus had been shipped half way around the world since being tested. There was also some concern about the difficulties of focussing the beam inside of a 6 Tesla, superconducting solenoid. (Somewhat less attention and calculation was devoted to the effect of the magnetic field of our solenoid upon other beam lines, until we started energizing it). It was also necessary to establish the delay between the electrical warning signal from LEAR and the intense pulse of particles at our detector. The test was extremely useful. After some adjustment, the beam line worked very well (with and without the 6 Tesla field) and one of our PPAC detectors (apparently damaged in shipping) was replaced with a backup.

The proton test also produced some interesting physics results on the side. We checked carefully with protons that we could adjust the effective thickness of our degrader over an adequate range (by changing the mixture of gasses in gas cells that the beam passes through) to insure that low energy protons (< 3 keV) would come out of the degrader. This involved measuring the range of protons in aluminum with a time-of-flight spectrometer similar to what we had used in the first of the 2 demonstration experiments. When we later repeated this measurement with antiprotons, we observed that the range of antiprotons in aluminum was different by about 6 percent.⁴ We had to compensate this shift in order to capture antiprotons in a trap. Apparently, this was the first observation of the so-called Barkas effect with protons and antiprotons, though PS 194 apparently observed the same effect a few weeks later with a different technique. Because of interest in this topic, a brief summary of our observations has been submitted for publication⁵ and is included as Sec. V. With more sustained study using this technique, much more accurate measurements of this effect could be made.

⁴ We were initially alarmed by two sudden shifts we observed during the first part of the proton test. It turned out that these shifts were small compared to the Barkas effect shift and seem to have been caused by an instrumental problem which was fixed before the proton test was completed. These shifts were not observed with antiprotons at all.

⁵ G. Gabrielse, X. Fei, L.A. Orozco, S.L. Rolston, R.L. Tjoelker, T.A. Trainor, J. Haas, H. Kalinowsky and W. Kells, "Direct Observation of the Barkas Effect Using Antiprotons and Protons", submitted to Physical Review Letters.

F. Large Increases in the Number and Lifetime of the Trapped Antiprotons, and Dramatic Cooling

Large increases in the number of trapped particles and the storage time within the trap, are summarized on the cover page of this progress report, along with the dramatic cooling which was observed. A more detailed account has been prepared for publication⁶ and is included in Sec. VI. The version supplied here is not yet final, but final form and/or a definite decision about publishing it at this time should be made before our progress report is presented orally.

G. Demonstration of Parasitic Operation at 105 MeV/c

During several weeks, the LEAR staff clearly demonstrated that they could first give us an intense pulse of antiprotons, and then slowly extract the remaining antiprotons to other users. LEAR loses only 1/7 of its antiprotons in the pulse and the remaining antiprotons are not heated very much because the beam is no longer bunched within LEAR. This is nice progress. (Initially, the beam was bunched into 4 bunches within LEAR, and one of these was kicked out to us. The bunching, coupled with the relatively inefficient stochastic cooling at 105 MeV/c, meant that approximately 1/2 of the antiprotons were lost from LEAR on the first extraction, and approximately 1/3 were lost on subsequent extractions.) Some grumbling accompanied the development of the new mode of operation, and users tended to blame the new operation for unrelated problems with the beam. Also, a laminated steering magnet would make the switching easier. Beyond doubt, the LEAR staff demonstrated that they could provide the great majority of the antiprotons to other users and still provide us with the intense pulse of antiprotons we need at the beginning of each spill. This is an ideal mode of operation for us most of the time.

II. Future Milestones and Beam Time

A. Why Not Just Use One Antiproton? (A Reduction in Energy by 10 Orders of Magnitude)

It is well known at CERN that we were able to store a single electron for more than 10 months while experimenting with it.⁷ It is also well known that we hope to obtain the highest precision mass measurement with a single antiproton in a trap by itself. We are thus asked frequently why we are bothering with more than 1 antiproton. The answer is simple. So far we have been focussed upon the difficult problem of slowing antiprotons from a kinetic energy of 5.9 MeV (a momentum of 105 MeV/c) down to 0.3 meV (milli-electron volts), which corresponds to 4.2 K. The energy of the antiprotons must thus be reduced by more than 10 orders of magnitude, as represented in the figure below.

(This figure was also shown as part of our original proposal.) We are now down in energy by 7 orders of magnitude, to below 1 eV. However, 3 orders of magnitude remain and we are not yet in full control

⁶ G. Gabrielse, X. Fei, L.A. Orozco, S.L. Rolston, R.L. Tjoelker, T.A. Trainor, J. Haas, H. Kalinowsky and W. Kells, "Antiprotons Cooled and Stored Below 1 eV", to be published.

⁷ G. Gabrielse, H. Dehmelt and W. Kells, Phys. Rev. Lett. **54**, 537 (1985).

of the cooling. The detection techniques used to develop and probe the cooling are very sensitive, but still consume the antiprotons in the process. We are still headed towards the goal of using and reusing 1 antiproton. However, this can not be attained in 24 hour demonstration experiments. What we need is as many of the parasitic pulses of antiprotons (describe in Sec. IG above) as we can possibly get. This will give us opportunity to feel our way into a new energy regime. When we do begin nondestructive RF measurements, it will be still necessary to replace antiprotons with protons in the trap to allow systematic comparisons.

B. Milestones Ahead

The description which follows is our best guess about what comes next. It should be remembered, however, that we are continuing into an energy range which has not yet been explored in any way. Unexpected difficulties could arise.

1. We will first try to understand and control the dramatic cooling we have observed. Our apparatus is being changed substantially during this shut down in response to what was observed this past fall. We will try to store antiprotons of energy below 1 eV for an hour or more.
2. The next step is to transfer the cold antiprotons into the region of the trap which is instrumented for nondestructive, radiofrequency measurements.
3. With success in 1. and 2. above, we will attempt a measurement of the inertial mass of the antiproton. We would expect a precision of 1 part in 10^6 or 1 part in 10^7 relatively quickly. This would already be a major advance, being from 50 to 500 times more accurate than previous measurements. If these three milestones are met before fall, we will be delighted. (Whether or not this is possible given the difficulty in obtaining antiprotons this year will be discussed in the next section.)
4. Further increases in precision will require that a hyperbolic Penning trap be added to our apparatus. We intend to catch in essentially the same trap we are using now and then, after cooling, transfer into the high precision trap. A high precision, hyperbolic trap has been constructed and space is available within our vacuum enclosure. The trap is identical to traps which will be used extensively at Harvard for electron and positron experiments, which means that its properties will be very well known. Work is also going on at Harvard to study the transfer of protons into such a trap. This trap has not yet been included in the apparatus at CERN in an effort to keep the experiment as simple as possible until we need this trap.
5. Obtaining a precision of 10^{-9} is difficult in a controlled environment such as the laboratory at Harvard constructed for such measurements. The situation at LEAR is much less under our control. Even with the tremendous help of the "self-shielding solenoid" described in Sec. IC, the fluctuating magnetic fields will be a troublesome. Since mass spectroscopy of this precision has never been done in such an environment, we do not know the extent of the problem or what will have to be done to solve it.

During the several years required to go after the highest precision, we expect that our consumption of antiprotons will not be very high.

C. Request for Beam Time

We are very concerned about the beam time situation this spring. It seems that a whole month is being taken by experiments at 2 GeV/c. A week of antiproton time will be lost due to the requirement to test a beam line with protons and no beam will be available at all during July. When the remaining time is split between 200 MeV/c and 100 MeV/c, this could mean that only 3 weeks of 100 MeV/c antiprotons will be available. The chance of our making substantial progress in this short of time is not very good. This seems very unfortunate, since we seemed to be poised to make such a substantially improved measurement of the inertial mass of the antiproton.

One help would be to make it possible for us to receive the antiprotons remaining at the end of a 200 MeV/c slow extraction to other users. This has been under discussion with the LEAR staff for a long time. In fact, the LEAR staff is at work on this problem. It seems certain that this will be possible, though it will take some engineering effort to automate the process sufficiently so that it can be implemented at any time, on any shift. We request that this mode of operation be developed with highest urgency. As the Crystal Barrel and the CP Violation experiment get set up and start to consume great quantities of antiprotons at 200 MeV/c, it seems essential that a mode of operation be developed whereby we can be successful in our measurement with minimal impact on other important experiments.

To be realistic, however, even if it becomes possible for us to experiment in the 3 weeks now contemplated for 200 MeV/c operation as well, there is still not very much low energy beam time available. If the committee and coordinator can devise a way to improve the prospects for low energy experiments this spring, it would be greatly appreciated.

Our requests for beam time for the rest of this calendar year are thus as follows.

1. During all 105 MeV/c operating time, we request to be parallel users, sharing the beam with one or two other users. Initially, while LEAR is retuning our line, and we are adjusting the new apparatus we would alternate spills with the other users. When the adjustments are completed, we would begin receiving one pulse of antiprotons at the beginning of each spill, with most of the antiprotons then being slowly extracted to the other users. Occasionally, if further tuning would be required we could switch back into a more normal shared mode. (The coordinator and the LEAR staff were very skilled in adapting to the needs of the users, last fall, as they fine tuned the schedule.)
2. During all 200 MeV/c operating time, we request that we be able to receive pulses of antiprotons at the end of each spill, using the new mode of operation being prepared by the LEAR staff.
3. We request that the Committee give high priority to development of parasitic modes of operation so that small-but-important experiments and large-but-important experiments can coexist with maximum physics output.
4. We request that the committee and Coordinator seek to increase the amount of antiprotons available at low energies.

III. The Antiproton Mass and CPT

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 known 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.

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 compilation²⁹ 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.

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.

The article

Phys. Rev. Lett. 57 (1986) 2504-7

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DIRECT OBSERVATION OF THE BARKAS EFFECT
USING ANTIPROTONS AND PROTONS

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Abstract

The difference in the range of protons and antiprotons in matter, an example of the Barkas effect, is observed in a simple time-of-flight apparatus. The ranges of 5.9 MeV antiprotons and protons differ by about 6% in a degrader made predominantly of aluminum. The measurement agrees well with theories which include "close collisions" and offers great potential for measurements of higher accuracy. A new technique is demonstrated, the use of an ion trap to extend energy loss measurements to transmitted projectiles with keV energies.

PACS: 34.50.Bw, 61.80.Mk, 29.70.Gn

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The availability of low energy antiprotons has triggered experimental and theoretical interest in comparing the interaction of protons and antiprotons with matter. Two examples are the calculation of the excitation of atomic inner shells by antiprotons¹ and the measurement of different cross sections for the double ionization of helium by protons and antiprotons.² The latter prompted theoretical studies^{3,4} which predict different distributions of secondary electrons for protons and antiprotons incident on He. In this Letter we report a new measurement. Antiprotons and protons were sent through aluminum to directly measure the Barkas effect, a difference in range for particles differing only in charge polarity. The Barkas effect is large, easily measureable and in good agreement with more recent theories which include the effect of "close collisions". The measurements were used to insure reliable capture of antiprotons in an ion trap for mass spectroscopy,⁵ as part of an experimental effort in progress at the Low Energy Antiproton Ring (LEAR) of CERN. (Antiprotons could be trapped only when the large observed shift in energy was compensated.) The uncertainties could be greatly reduced with more sustained study, especially if protons and antiprotons were compared relatively quickly, offering the possibility of more rigorous tests of various theories.

Barkas and collaborators⁶ first used emulsion track studies to observe the difference between the energy loss processes for π^+ and π^- , and also for Σ^+ and Σ^- . For a particle of charge Z and velocity v passing through a target of atomic number Z_t , the stopping power S may be written as

$$S = -\frac{dE}{dx} = \frac{4\pi e^4 N_0}{mv^2 A} Z^2 Z_t (L_0 + L_1 Z + L_2 Z^2). \quad (1)$$

Here, N_0 is Avogadro's number, m is the electron mass and A is the atomic number of the target material. The dependence upon the projectile charge Z is characterized by the functions L_0 , L_1 and L_2 , which depend upon the projectile velocity and the target material. Both the leading term, proportional to L_0 and Z^2 , and the next even order term, proportional to L_2 and Z^4 , are independent of the sign of Z . A nonzero L_1 , however, indicates a Z^3 dependence of the stopping power which is different in sign for projectiles of opposite charge. A positive L_1 indicates more energy loss and hence a smaller range for a positive particle than for a negative particle, all other conditions being equal.

The simple measurements reported here illustrate how direct studies of the Barkas effect can be carried out when projectiles differing only in sign of charge are sent through the same material. With protons and antiprotons of the same energy, observed differences in the stopping power and range arise directly from L_1 (and higher order terms odd in Z , neglected here) and not from differences in mass or velocity. The effect of the terms of even order in Z cancel out directly. Available experimental data with positive and negative muons^{7,8} and with a series of positive ions⁹ so far indicate that L_1 is positive. Theoretical investigations¹⁰ agree qualitatively. However, unresolved controversies about the collision mechanism can provide theoretical differences of a factor of 2 or more in analytical forms, with additional and larger discrepancies arising from numerical calculations.

The apparatus used (Fig. 1) is very similar to the apparatus we used with 21 MeV antiprotons several years ago.¹¹ Antiprotons or protons with a fixed kinetic energy of 5.9 MeV, extracted from LEAR through a thin titanium window, enter this apparatus from below at a rate kept less than 3 kHz. To vary the energy of the projectiles a small amount, they are sent through two gas cells indicated in the figure. Either SF_6 or N_2 at a pressure of 1 atm was kept flowing slowly through gas cell 1. The energy loss in the N_2 was smaller than the energy loss in the SF_6 by approximately 250 keV, so the energy of the protons and antiprotons leaving gas cell 1 could be changed discontinuously by this amount. A mixture of SF_6 and He , also at 1 atm, was sent through gas cell 2. The mix could be adjusted continuously with electronically controlled flow meters, making the energy of the antiprotons leaving gas cell 2 to also be continuously adjustable over an additional 500 keV when the mixture was changed from 0 % SF_6 (i.e. 100 % He) to 100 % SF_6 (i.e. 0 % He). These energy shifts were calibrated using the variable energy proton beam of a tandem accelerator to produce range curves such as Fig. 2, as discussed later. The energy loss was linear in the percentage of SF_6 .

Two parallel plate avalanche counters (PPAC) located between the two gas cells determine when a proton or antiproton enters the apparatus with near unit efficiency and nanosecond resolution. Each detector is comprised of 5 strips oriented in the two transverse directions to provide a position sensitive readout of the beam position with 2.5 mm resolution. Typically, the beam is focussed into a spot diameter less than 6 mm (full width half maximum). An active coincidence of the center strips in each PPAC makes it possible to select only protons or antiprotons which pass through a square of side 2.5 mm, centered on the vertical symmetry axis of the apparatus, to avoid counting poorly steered particles. The antiprotons slow in several layers of material needed for the trapping experiments being prepared. (For example, vacuum windows and radiation shields are required to allow cooling the apparatus to 4.2 K.) Each layer is listed in order in Table I, along with the equivalent thickness of aluminum and the approximate energy loss in each layer.¹² The antiprotons stop and are detected with near unit efficiency in a channel plate detector located several centimeters down beam. The final degrader window and the channel plate are biased as indicated to minimize the probability of detecting a secondary electron liberated from the aluminum. Coincidences of the PPAC detectors with the channel plate are divided by the number of PPAC counts to get a measure of the fraction

of the incident particles transmitted through the degraders between. (A great deal more information is measured in addition to these ratios. Time-of-flight spectra for the transmitted particles are also recorded, making it possible to compare the energy spectra of the transmitted protons and antiprotons). From Table I, most of the slowing, nearly 4 MeV, occurs in the final aluminum layer.

Table I. Matter Traversed by Protons and Antiprotons

Material	Equivalent Thickness of Aluminum ¹² in μm	Energy Loss ¹² (MeV)
10 μm Ti	16	0.21
gas cell 1 with N_2 (SF_6)	4.4 (23)	0.06 (0.31)
PPAC 1	11	0.16
PPAC 2	11	0.16
gas cell 2 with He (SF_6)	1.4 (34)	0.02 (0.52)
10 μm Ti	16	0.24
51 μm Mylar	31	0.52
10 μm Ti	16	0.27
117 μm Al	117	3.70
Total	224 (275)	5.34 (6.09)

The points in Fig. 2 are two measurements of the number of transmitted projectiles versus the effective thickness of the degrader. The left curve is for protons, the right curve is for antiprotons. The vertical scale is proportional to the coincidence signal divided by the number of incident projectiles as described earlier. A small and flat pion background of $\approx 10\%$ (from annihilation pions striking the channel plate) was subtracted off in the case of the antiprotons. The horizontal scale indicates the fraction of SF_6 in gas cell 2 with either N_2 in the first gas cell (tick marks above the axis) or with SF_6 in the first gas cell (tick marks below the axis). The horizontal scale thus essentially represents the "thickness" of the degrader. Increasing the aluminum thickness by 51 μm would cover the same range covered by this scale. Alternatively, the horizontal scale represents the relative energy of the particles incident on the degraders. The entire horizontal scale corresponds to a shift of approximately 750 keV in the incident energy. The shift of the proton range curve as a function of incident proton energy was used to calibrate the gas cells.

The error bars on the measured points in Fig. 2 represent the largest variations observed in the measured points over several hours. This scatter is almost entirely systematic, being correlated with beam intensity, beam steering, etc. It could likely be disentangled with beam time devoted to this purpose. The size of the points themselves represent the short term repeatability over several minutes. The proton and antiproton curves have similar shape, as illustrated by the identical smooth curves sketched through the measured points, but the antiproton curve is shifted by $150 \pm 20 \text{ keV}$. Several corrections and additional uncertainties must be included. The LEAR staff measured the difference in beam energy between protons and antiprotons extracted from LEAR to be $13 \pm 12 \text{ keV}$. Temperature differences in the degraders between the proton and antiproton measurements contribute $31 \pm 12 \text{ keV}$. Uncertainties in the calibrations of the first and second gas cell contribute ± 30 and $\pm 20 \text{ keV}$, respectively.¹³ The net result is that the energy lost by 5.9 MeV protons is greater by

$$\Delta E = 194 \pm 45 \text{ keV} \quad (2)$$

than the energy lost by 5.9 MeV antiprotons. The aluminum equivalent for this energy difference is $\Delta R = 14 \mu\text{m}$ and

$$\frac{\Delta R}{R} = 5.6 \pm 1.4\% \quad (3)$$

is the equivalent fractional range difference in aluminum, the range being larger for antiprotons.

To quote the above range difference for aluminum and to compare with theoretical values, we initially model our degrader as a piece of aluminum approximately 250 μm thick. This is the sum of the equivalent Al thicknesses from Table I. The formula given by ARB theory¹⁴ gives a fractional range difference of 3.2% which is somewhat lower than our measured value. However, Linhard included the contributions from close

collisions which are absent in ARB theory and estimated that the Barkas effect was approximately twice that of ARB theory.¹⁵ To accommodate this effect, Ritchie and Brandt¹⁶ adjusted their original choice of cut-off at small impact parameters to make the L_1 larger. Both the Linhard theory and the adjusted ARB theory seem to agree well with our measurement, though we had some difficulty extracting precise theoretical numbers for comparison. Having made a favorable comparison with theory, we use the Linhard theory to estimate that modeling the matter traversed by the beam as a single piece of aluminum could cause an error as large as ± 20 keV, somewhat smaller than the uncertainty from other sources. We can thus consider Eq. (3) to be the measured range in Al provided the quoted uncertainty is increased to ± 50 keV. The reason that the Barkas effect occurs primarily in the aluminum is that until they enter the final aluminum degrader at approximately 4 MeV (Table I), the antiprotons and protons travel rapidly enough so that contributions to the Barkas effect are small.

Finally, we illustrate in Fig. 3 a promising new technique for studying the interaction of charged particles with matter which has implications beyond the study of the Barkas effect. A 6 Tesla magnetic field was added in the direction of the incident particles and the channel plate detector was replaced with an open access Penning trap.¹⁷ Antiprotons entered this trap through the final aluminum degrader window which also served as one electrode of the trap. The number of antiprotons captured in this trap, normalized to the number of incident antiprotons in the pulse from which these were trapped, is plotted as a function of the gas mixture. In this particular case, the number of antiprotons was measured by releasing them from the trap and detecting annihilation pions in surrounding scintillators, but other detection methods (eg. a channel plate) could be used to detect protons as well as antiprotons. The number of low energy antiprotons clearly peaks with optimal tuning of the gas cells. (This optimal tuning is also observed with the time-of-flight spectrometer of Fig. 1, with 10^{-4} of the incident antiprotons emerging from the degrader with keV energies, per keV of exit energy.) The unique feature of the trap technique is that only particles with energies below 3 keV could possibly be caught in the trap, this was the depth of the potential well, so that transmitted particles of extremely low energy could be studied. Unfortunately, small changes were made to the degraders when the trap was added which shifted the zero of the horizontal axis for the low energy distribution (Fig. 3) relative to that in Fig. 2, so that it is not possible to deduce from this measurement the relative location of the low energy peak in Fig. 3 relative to the half intensity point of Fig. 2.

In summary, the Barkas effect is detected when 5.9 MeV protons and antiprotons are sent through the same aluminum window. Because the proton and antiproton differ only in charge, not in either mass or velocity, the Barkas effect is directly measured. Because of the limited beam time for this measurement, the uncertainties are entirely systematic and could be reduced substantially. Moreover, the use of a simple trap following the degraders could make it possible to explore new, extremely low energy regions about which very little is known.

Acknowledgements

We are grateful to CERN and the excellent LEAR staff for providing the protons and antiprotons for this measurement. Calibration of the gas cell and other tests with protons were performed at the tandem accelerator of the University of Washington. This work was supported by NSF, NBS, AFOSR, DOE and the BMFT.

Figure Captions

- Fig. 1 Time-of-flight apparatus.
 Fig. 2 Normalized fraction of antiprotons detected after the degrader showing the difference in energy loss and range of protons (left) compared to antiprotons (right). The horizontal scale indicates the gas mixture used to tune the energy of the proton beam. The size of equivalent changes in the energy of the incident particles and the thickness of the aluminum degrader are indicated by the arrows.
 Fig. 3 Normalized number of antiprotons caught in an ion trap only 3 keV deep. The horizontal scale is identical to that in Fig. 2 but is shifted by a small amount.

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Fig. 1

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Fig. 2

Fig. 3

STORED ANTIPROTONS COOLED BELOW 1 eV

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Abstract

More than 60,000 antiprotons are stored in a Penning trap from a single pulse of 5.9 MeV antiprotons from LEAR, with a storage lifetime exceeding 50 hours. The trapped antiprotons initially range in energy between 0 and 3000 eV, but can be cooled dramatically to below 1 eV. The cooling may be due to collisions with cold electrons, but the mechanism has not yet been proven.

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The Low Energy Antiproton Ring (LEAR) at CERN is able to store 5.9 MeV antiprotons, the lowest energy antiprotons available for experiment. Just over two years ago, antiprotons more than 1000 times lower in energy were briefly stored in an ion trap.¹ These antiprotons came from LEAR, but were slowed by passing them through matter. Of order 300 antiprotons were stored in an ion trap, with a storage lifetime of a few hundred seconds. Their energy was spread between 0 and 3 keV.

For many experiments it is desirable to obtain more antiprotons, longer lifetimes and lower energies. A much more accurate measurement of the inertial mass of the antiproton, for example, becomes feasible with antiproton energies of order 1 meV.² This would be one of only a few precise tests of CPT invariance, the only such test with baryons.³ With even lower energies there are plans to measure the gravitational force on antiprotons.⁴ It may even become possible to produce and study antihydrogen,⁵ perhaps allowing a measurement of the gravitational force without the severe competition of electrical forces.⁶ We have now stored more than 60,000 antiprotons in a Penning trap, with a storage lifetime exceeding 50 hours. This represents more than a 200-fold increase in the number of trapped antiprotons and more than a 700-fold increase in storage time. The trapped antiprotons initially range in energy between 0 and 3 keV, and can be stored for days without losing appreciable energy. Under reproducible conditions, however, of order 20,000 antiprotons could be cooled below 1 eV within approximately 20 seconds. This dramatic cooling of the energy distribution (by more than a factor of 1000) may be due to collisions with trapped electrons, but this has not yet been proven experimentally.

Before ejection to this experiment, LEAR was filled with 1 to 4×10^9 antiprotons, cooled stochastically at 5.9 MeV. These antiprotons could then be ejected for us in pulses 300 ns long, approximately 1/7 of the antiprotons in LEAR leaving in each successive pulse. The antiprotons left the LEAR beamline directed upwards through a $10 \mu\text{m}$ titanium vacuum window. The window and all of the rest of the apparatus is located within a superconducting solenoid which produces a 6 Tesla field parallel to the beam direction. The antiprotons pass through a parallel plate avalanche counter (PPAC) which is position sensitive, with 2.5 mm resolution. An antiproton pulse is typically focussed to a spot diameter of 6 mm (full width half maximum). Immediately before and after the PPAC, the antiprotons pass through gas cells, one boundary of which is a second $10 \mu\text{m}$ titanium window. The energy of the antiprotons can be tuned by approximately 750 keV by changing the mixture of gasses in these two gas cells.⁷

Antiprotons next pass through a $51 \mu\text{m}$ mylar radiation shield and then enter a completely sealed vacuum enclosure from below through a third $10 \mu\text{m}$ titanium window (Fig. 1). At this point they still have a kinetic energy of approximately 3.7 MeV. The sealed vacuum enclosure is cooled to 4.2K via a thermal coupling to a liquid helium dewar located above. Final slowing of the antiproton beam occurs within the $117 \mu\text{m}$ aluminum window. The beam energy is tuned to maximize the number of low energy antiprotons emerging from this window.⁷ The aluminum window and the cylindrical electrodes are grounded as the pulse of antiprotons enters the trap electrodes. A flat plate above is biased at -3keV to turn around antiprotons with kinetic energies (along the beam axis) below 3 keV. After the pulse of antiprotons is within the trap electrodes, the potential of the aluminum degrader is quickly switched⁸ to -3kV, completing the Penning trap and containing the particles.

After a preset holding time (ranging from 1 ms to 2.7 days so far) the potential of the upper flat plate is slowly and linearly ramped through 0 volts over 0.1 sec, a variation of the technique developed for lower energies.⁹ The period of an antiproton's oscillation back and forth along the direction of the magnetic field is expected to be short compared to 0.1 sec, so that antiprotons with energies exceeding the ramp voltage simply leak out of the trap. They annihilate upon striking an electrode, producing on average 3.5 charged pions. These are detected in 6 plastic scintillators which surround the dewar for the superconducting magnet. We obtain 4 separate coincidence signals when one (or more) to four (or more) of our 6 scintillators simultaneously detect a pion. One of these signals is recorded in a multiscaler which starts counting when the voltage ramp starts. Since the voltage ramp is linear, the multichannel spectrum is directly an energy spectrum for the trapped antiprotons. The energy measured by this technique is the energy of motion in the direction of the incident beam and the magnetic field. (The antiprotons' transverse energy is stored in the cyclotron motion of the antiprotons and is not measured here.) The efficiency for producing one (or more) hits in our scintillators from an antiproton annihilation in the trap is estimated to be above 90% (but has not yet been measured precisely) and the ratio of two (or more) hits to one (or more) hits is measured to be 0.358. In what follows, we will display only spectra for one (or more) hits and assume 100% efficiency to avoid overstating the number of trapped and cooled antiprotons.

Fig. 2 shows an energy spectrum for antiprotons trapped from a relatively small pulse of antiprotons from LEAR, and held 2.7 days before the potential of the upper plate electrode was ramped from -3kV to +4 volts. The nearly 4000 detected annihilations are plotted as a function of the potential of the plate at which the annihilations occurred. The spectrum cuts off at 0 volts and falls off at higher kinetic energies as the antiproton energy approaches the well depth. As many as 60,000 antiprotons have been detected in such spectra after 100 seconds in the trap, depending upon the number of antiprotons in the pulse from LEAR and upon how well the beam is focussed and steered. This number could likely be doubled with a longer pulse of antiprotons from LEAR. Based upon the number of antiprotons leaving LEAR, we capture antiprotons from LEAR with an efficiency exceeding 10^{-4} . The actual efficiency is certainly higher, since

all of the antiprotons which leave LEAR do not arrive at our experiment (due to the rise and fall time of the kicker, for example), but the actual number of antiprotons arriving at our experiment has not been measured.

Antiprotons were routinely held for up to an hour, with no clear loss of particles. Since we were reluctant to use our limited beam time doing long lifetime tests, however, the lifetime of the trapped antiprotons was not investigated very thoroughly. The one case where antiprotons were held longer is that shown in Fig. 2. Comparing the nearly 4000 antiprotons remaining after 2.7 days to the size of the initial PPAC signal for normalization, it seems safe to say that the confinement lifetime is greater than 50 hours. Longer lifetimes have been achieved in various storage rings, but only with antiprotons of much higher energy, for which the cross sections for collision and annihilation with background gas atoms are very much smaller. For comparison, LEAR, though operating at 5.9 MeV (higher by 2000) has a storage lifetime of only an hour (smaller by at least 50). Our long storage times at low energy are made possible by the extremely good vacuum in our sealed enclosure at 4.2 K. Although no active pumping is used, the container itself and the electrodes are extremely effective cryopumps.¹⁰

The energy distribution of the antiprotons stored for 2.7 days (Fig. 2) is similar to the distribution of antiprotons held for shorter times. After 100 seconds in the trap, the spectra differ principally by having a sharper cutoff at 0 volts. Also, the most intense pulses of antiprotons from LEAR (typically only the first pulse after LEAR was filled) produce a distribution with a slight peak below 100 volts. Dramatic cooling of the antiprotons within the trap occurred, however, if the antiprotons were loaded into the trap exactly as before except that a -20 volt potential was applied on the central electrode, marked A in Fig. 1. The energy distribution is so significantly narrowed (by more than a factor of 1000) that an example in Fig. 3 is plotted on a greatly expanded scale. The antiprotons were held for 30 seconds to allow cooling, then the potential on the upper plate was slowly lowered from -3000 to -50 volts. At 100 seconds after capture, the potential was ramped linearly through zero. The energy distribution is shown in Fig. 3a and the potential applied to the top end plate electrode is shown in Fig. 3b. Only the last two volts of the ramp applied to the upper plate electrode are shown, because no antiprotons are detected until after the electrode is below 1 volt. In fact, many of the antiprotons detected may have had much lower energies. Antiprotons continue to annihilate for 10 ms after the potential crosses zero. The time scale is shown on the upper horizontal axis of Fig. 3. These late arrivals seem to be antiprotons so low in energy that their flight times before annihilating are important, as is the rate of change of the ramp potential and the small hole in the upper end plate. For comparison, an antiproton with an energy of 0.35 meV (corresponding to 4.2 K) travels at a velocity of 26 cm/ms, thus traveling twice the length of the trap in 1.3 ms when the electrodes are all grounded. Peaks of approximately this spacing in time seem to be present in the cooled distribution, but are not understood, being complicated by the changing potential. Also noteworthy is that this cooled spectrum contains 20,000 antiprotons, fully 1/3 of the maximum number we ever observed in the trap.

We were looking for electron buffer gas cooling which we initially proposed could be the most effective cooling mechanism in the trap.¹¹ In a recent discussion of cooling possibilities¹², cooling times of 1 second and less were estimated for trapped antiprotons colliding with an achievable density of cold electrons stored in the same trap. Unfortunately, we have not yet been able to establish whether electron cooling is or is not providing the extremely effective cooling we observe. It is likely that 10^8 antiprotons going through the aluminum window will liberate many electrons, ions and neutral atoms in an initial pressure burst. Electrons could be trapped in the same well with the antiprotons. Positive ions could be trapped within the -20 volt region, provided that a collision mechanism is available to remove energy from them when they first pass through the well. Trapped electrons would cool into thermal equilibrium at 4.2 K via synchrotron radiation, which has a time constant of 0.1 sec, when the density is high enough to couple the various motions of the electrons in the trap. The ions do not cool readily and thus should keep their initial energies for a long time. Antiprotons could cool via collisions with the electrons or ions, transferring energy more efficiently in collisions with ions, though no ions are presumably in the region of the trap where the cooled antiprotons eventually seem to reside (as will be discussed). Other cooling mechanisms, such as adiabatic cooling and evaporative cooling are also being considered, but do not seem able to account for cooling by such a large factor.

Several observations seem relevant to understanding the cooling mechanism. First, the dramatic cooling only occurs during the first 7 or 8 pulses from LEAR after LEAR is refilled. Successive pulses from LEAR are less intense, thus the number of electrons, ions, and neutrals liberated from the aluminum degrader and its surface presumably declines as well. Second, the cooled antiprotons we observe seem to be mostly located in the upper well, in the region indicated in Fig. 1. After arranging that these escape from the trap as described, we ground the -20 volt electrodes, to permit any low energy antiprotons in the well nearest the aluminum degrader to enter the big well. When we ramp down the potential of the upper plate again, however, we rarely detect additional antiprotons. (This interpretation presupposes that the -20 volt well is not completely filled with ions so that space charge cancels the effect of this well.) Third, the dramatic cooling happens when a -20 volt potential is applied to a central electrode (marked A in Fig. 1) before the antiprotons are trapped. Applying the same potential to the up beam electrodes B and C as well, makes little difference. However, applying the -20 volts only to B or only to C produces no cooling at all. We do not

understand this, but it may be related to the charging of a MACOR spacor (cross hatched in Fig. 1) which is exposed within the upper region of the trap. Fourth, after holding antiprotons for 300 seconds we repeatedly measure distributions such as that shown in Fig. 3. However, if we wait until 900 seconds the antiprotons no longer show up in our energy spectrum. It is not clear whether the antiprotons are annihilating or whether the antiprotons are cooled to such low energies that we are unable to extract them from the trap because of stray potentials which are present. We have some tantalizing but ambiguous hints that the latter is the case. Also, if we change the electrodes at -20 volts to 0 volts at 30 seconds after capture, we observe several thousand particles remaining at the end of 900 sec. Finally, if we instead apply +20 volts to the central electrode A, the trapped antiprotons again do not show up in the measured energy spectrum.

In summary, the number of trapped antiprotons with energies below 3 keV has been increased by 200 and their lifetime has been increased by more than 700. Dramatic cooling has been observed whereby the spread in the energies of the trapped antiprotons is reduced by more than 1000. Although, electron cooling was anticipated, the cooling mechanism has not yet been established. Since approximately 1/3 of the trapped antiprotons are cooled and remain after 300 seconds, prospects for low energy studies with antiprotons are greatly enhanced. It may already be possible to extract and accelerate the low energy antiprotons to produce a (weak) antiproton source which is very monoenergetic.

Acknowledgements

We are grateful to CERN and the excellent LEAR staff for providing the protons and antiprotons for this measurement. This work was supported by NSF, NBS, AFOSR and the BMFT. Tests with protons were performed at the tandem accelerator of the University of Washington, which is supported by DOE.

Figure Captions

Fig. 1 Trap apparatus.

Fig. 2 Antiproton energy spectrum for antiprotons held 2.7 days.

Fig. 3 Cooled antiproton energy spectrum (a) and the potential on the upper end plate electrode (b).

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Fig. 2

Fig. 3