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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		Final Report 01 Jul 88 - 30 Sep 93

4. TITLE AND SUBTITLE

Antiproton studies in penning traps

5. FUNDING NUMBERS

AFOSR-88-0306

2

6. AUTHOR(S)

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AFOSR-TR- 93 0943

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NE
110 DUNCAN AVENUE, STE B115
BOLLING AFB DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

2301/DS

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

UNLIMITED

This document has been approved for public release and sale; its distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

SEE ATTACHED SUMMARY

14. SUBJECT TERMS	15. NUMBER OF PAGES
	17
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclass	unclass	unclass	UL

I. PROJECT SUMMARY

Antiprotons are produced in giant accelerators with typical energies measured in GeV. In the unique LEAR facility of CERN. such antiprotons are decelerated to and cooled at an energy of 5 MeV. The experiments described in this proposal made it possible to slow. store and study antiprotons at dramatically lower energies. 10^{10} times lower than ever realized before. Antiprotons from LEAR are slowed to several keV by sending them through a metal degrader window of a precisely chosen thickness. They are then captured in a specially designed Penning trap. Once inside the trap, collisions with extremely cold electrons dramatically lower the energy of the trapped antiprotons to thermal equilibrium at 4.2 K. Antiprotons have now been stored for months in thermal equilibrium at 4.2 K, which requires a vacuum better than 5×10^{-17} Torr. The first precision measurement at this new, low energy frontier is a comparison of the inertial masses of the antiproton and proton at an accuracy more than 1000 times greater than was achieved in earlier experiments. The accurate mass spectroscopy is greatly facilitated by the invention of self-shielding superconducting solenoid system which has likely applications to MRI imaging. This is by far the most sensitive test of CPT invariance with a baryon system and is one of the most accurate tests of CPT invariance done with any particle system. We have subsequently demonstrated and are currently exploiting a measurement precision which is improved by an additional factor of 40. The techniques and apparatus developed are being extended to the mass spectroscopy of other systems. We recently demonstrated that extremely cold antiprotons can be transported large distances by transporting trapped electrons across the continental United States in an apparatus similar to that used to contain low energy antiprotons. With an eye to the future, an increasing effort is aimed at developing techniques to eventually make usable amounts of antihydrogen by recombining cold, trapped plasmas of positrons and antiprotons. Already, extremely cold protons and electrons have been trapped in neighboring traps and passed through each other.

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Final Technical Report to the Air Force Office for Scientific Research
Period: 1 July 1988 through 30 September 1993
Grant Number: AFOSR 88-0306

ANTIPROTON STUDIES IN PENNING TRAPS

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I. PROJECT SUMMARY

Antiprotons are produced in giant accelerators with typical energies measured in GeV. In the unique LEAR facility of CERN, such antiprotons are decelerated to and cooled at an energy of 5 MeV. The experiments described in this proposal made it possible to slow, store and study antiprotons at dramatically lower energies, 10^{10} times lower than ever realized before. Antiprotons from LEAR are slowed to several keV by sending them through a metal degrader window of a precisely chosen thickness. They are then captured in a specially designed Penning trap. Once inside the trap, collisions with extremely cold electrons dramatically lower the energy of the trapped antiprotons to thermal equilibrium at 4.2 K. Antiprotons have now been stored for months in thermal equilibrium at 4.2 K, which requires a vacuum better than 5×10^{-17} Torr. The first precision measurement at this new, low energy frontier is a comparison of the inertial masses of the antiproton and proton at an accuracy more than 1000 times greater than was achieved in earlier experiments. The accurate mass spectroscopy is greatly facilitated by the invention of self-shielding superconducting solenoid system which has likely applications to MRI imaging. This is by far the most sensitive test of CPT invariance with a baryon system and is one of the most accurate tests of CPT invariance done with any particle system. We have subsequently demonstrated and are currently exploiting a measurement precision which is improved by an additional factor of 40. The techniques and apparatus developed are being extended to the mass spectroscopy of other systems. We recently demonstrated that extremely cold antiprotons can be transported large distances by transporting trapped electrons across the continental United States in an apparatus similar to that used to contain low energy antiprotons. With an eye to the future, an increasing effort is aimed at developing techniques to eventually make usable amounts of antihydrogen by recombining cold, trapped plasmas of positrons and antiprotons. Already, extremely cold protons and electrons have been trapped in neighboring traps and passed through each other.

II. INTRODUCTION

Nearly seven years ago AFOSR began funding the antiproton research and mass spectroscopy, which are the subjects of this proposal. There was some risk insofar as we were inexperienced in doing experiments with antiprotons. Without the timely AFOSR support, it is unlikely that this program would have gotten started at all. As it was, in the first three years we demonstrated (in a 24 hour antiproton run) that we could slow antiprotons below 3 keV by sending them through a thin window of matter. In a second 24 hour demonstration experiment, we managed to capture a few antiprotons in the small volume of an ion trap.[1] When the preceding proposal was written three years ago, a dedicated beam line was under construction at the Low Energy Antiproton Ring (LEAR) for our use in measuring the inertial mass of the antiproton and doing related low energy experiments. (LEAR is a unique facility of the CERN Laboratory in Geneva, Switzerland which was able to provide us with antiprotons as low in energy as 6 MeV).

Progress over the last three years (Sec. III.A) has been equally satisfying. Four major steps forward can be distinguished. The first is that we studied in more detail the slowing of antiprotons in matter, observing the difference in scattering between the antiprotons and protons which is known as the Barkas effect.[2] In a second step, we captured antiprotons slowed below 3 keV with the number of trapped antiprotons increased by many orders of magnitude over that observed in the demonstration experiment. These antiprotons were then cooled via collisions with cold electrons which awaited the arrival of antiprotons in the trap.[3] Eventually, we were able to realize more than 10^5 trapped antiprotons, cooled to thermal equilibrium at 4.2 K, with storage lifetimes exceeding 3.4 months.[4] A new, low energy frontier is thus opened up insofar as this energy is more than 10 orders of magnitude lower than the lowest energy at which antiprotons are stored in any other apparatus or experiment. The storage time requires a vacuum better than 5×10^{-17} Torr. In the third step forward we were able to realize a superconducting solenoid system which effectively shields our antiprotons from fluctuations in the ambient field of the accelerator environment. In our proposal three years ago, we had suggested that a self-shielding superconducting solenoid we had invented[5] should substantially reduce fluctuations in the ambient field at the location of our experiment. We have now demonstrated that this experimentally.[6] Our self-shielding solenoid system reduces the spatially uniform fluctuations in the ambient field by a factor of 156. With the extremely cold antiprotons located in the extremely stable magnetic field, we were able to make the fourth step forward. The inertial masses of antiproton and proton were compared and found to be the same[4] at an accuracy of 4×10^{-8}. This is a 1000 times more accurate than was achieved in all

[1] G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker and T.A. Trainor, Phys. Rev. Lett. 57, 2504, (1986).

[2] G. Gabrielse, X. Fei, L.A. Orozco, S.L. Rolston, R.L. Tjoelker, T.A. Trainor, J. Haas, H. Kalinowsky and W. Kells, Phys. Rev. A (Rapid Comm.), 40, 481 (1989).

[3] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor and W. Kells, Phys. Rev. Lett. 63, 1360 (1989).

[4] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor and W. Kells, Phys. Rev. Lett. 65, 1317 (1990).

[5] G. Gabrielse and J. Tan, J. Appl. Phys. 63, 5143 (1988).

[6] G. Gabrielse, J. Tan, P. Clateman, L.A. Orozco, S.L. Rolston, C.H. Tseng and R.L. Tjoelker, J. Mag. Res. 91, 564 (1991).

previous measurements.[7,8,9,10] The new ratio has been interpreted[11] as setting a limit on possible differences in the gravitational properties of the proton and antiproton because of our observed absence of a gravitational red shift. Also we measured the protein-to-electron mass ratio. Our ratio agrees at comparable accuracy with the corrected value of Van Dyck. et.al.[12] and disagrees with their earlier measurement[13] which had a systematic problem. Many publications (Sec. III.B) and invited talks (Sec. III.C) acknowledge the AFOSR support, and this research work was often reported in the popular scientific press (Sec. IX).

The project description (Sec. IV) closely resembles the initial proposal made to CERN in 1985, which was the basis of previous proposals to AFOSR. Crucial elements have now been demonstrated and are now being utilized and refined in pursuit of ever increasing accuracy in the comparison of the inertial masses of the antiproton and proton. Slowing antiprotons in matter (Sec. A), capturing antiprotons in an ion trap (Sec. B), electron cooling of antiprotons (Sec. C), cancelling fluctuations in the ambient magnetic field (Sec. D) and comparing antiproton and proton masses (Sec. E) have all been demonstrated for the first time and are now in use. The quest for even higher precision is summarized in Sec. F. A cyclotron line width narrower by a factor of 40 than the reported accuracy of 4×10^{-8} mentioned above, has already been observed. Recently initiated studies which could eventually lead to measurements of the antiproton magnetic moment are mentioned in Sec. G. Finally, the possibility of using the cold antiprotons to produce antihydrogen atoms[14] is discussed in Sec. H. This is theoretical work which was published after the last AFOSR proposal three years ago. At CERN we are being encouraged to see just how many antiprotons can be caught in a Penning trap for possible use in antihydrogen production. Already we have demonstrated that more than 10^5 antiprotons can be sequentially stacked in the Penning trap, one pulse of antiprotons after another being cooled by the electrons into a small storage region of the catching trap. We will do more such experiments, whenever we can do so without compromising progress towards our goal of comparing the inertial masses of the antiproton and proton to better than 1 part in 10^9.

From the outset, the funding for this program was provided jointly by two agencies. Support from AFOSR is primarily for two postdoctoral research associates and CERN expenses as described in Sec. VI. Owing to the time constraints and the necessity to perform much of the experiment at CERN in Switzerland, the full time participation of postdoctoral research associates is essential to the antiproton program. The complementary support from NSF is outlined in Sec. VII. It primarily covers the effort to prepare apparatus and develop techniques at Harvard, which are transferred to CERN when ready. Precision experiments with Penning traps are "table top" experiments. The difference in the antiproton experiments is that the table top must operate remotely and must move back and forth to Geneva, Switzerland. The tight accelerator time schedule also means that the experiment must be engineered more carefully for reliability. Also, devaluation of the

[7] A. Bamberger, U. Lynen, H. Piekarz, J. Piekarz, B. Povh, H.G. Ritter, G. Backenstoss, T. Bunaciu, J. Egger, W.D. Hamilton and H. Koch, Phys. Lett. **33B**, 233 (1970).

[8] E. Hu, Y. Asano, M.Y. Chen, S.C. Cheng, G. Dugan, L. Lidofsky, W. Patton, C.S. Wu, V. Hughes and D. Lu, Nucl. Phys. **A254**, 403 (1975).

[9] P. Roberson, T. King, R. Kunselman, J. Miller, R.J. Powers, P.D. Barnes, R.A. Eisenstein, R.B. Sutton, W.C. Lam, C.R. Cox, M. Eckhause, J.R. Kane, A.M. Rushton, W.F. Vulcan and R.E. Welsh, Phys. Rev. C **16**, 1945 (1977).

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[11] R.J. Hughes and M.H. Holzscheiter, Phys. Rev. Lett., **66**, 854 (1991).

[12] R.S. Van Dyck. Jr., F.L. Moore, D.L. Farnham and P.B. Schwinberg, Bull. Am. Phys. Soc. **31**, 244 (1986).

[13] R.S. Van Dyck. Jr., F.L. Moore, D.L. Farnham and P.B. Schwinberg, Int. J. Mass Spectrom. Ion Processes **66**, 327 (1985).

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dollar relative to the Swiss franc makes it extremely expensive to work and live in Geneva. These complications add to the manpower and funding requirements, even though manpower and funding requirements are still far below the typical high energy physics experiment at such facilities. The unique cooperation between AFOSR and NSF continue to make this antiproton research possible.

It is extremely important to stress the delicate position we are in at CERN. As mentioned, our unique experience and access to low energy antiprotons makes it possible for us to do antiproton experiments which cannot now be done at any other facility in the world. Because of the fundamental character of our research goals and the rapid experimental progress we have made, these experiments are very highly regarded at CERN. We are thus given antiprotons ahead of many European research groups, despite the fact that CERN is a cooperative facility of European countries and that the United States is not a member and does not support CERN. On the good side, this means that the extremely high cost of producing the required antiprotons does not need to be covered by the U.S. funding agencies. On the bad side, CERN does not otherwise support the experiments in any way and we cannot allow our rapid progress to slow if we expect this unique opportunity to continue.

III. WORK SUPPORTED BY THE AFOSR

A. SUMMARY (Last Three Years)

It is a great pleasure to summarize the progress made in the last three years. since the antiproton studies have gone just about as well as one could dare to hope. The progress is especially satisfying since this three year period began shortly after my research group relocated from the University of Washington in Seattle to Harvard University. Not long before, we had demonstrated in a 24 hour antiproton run that we could slow antiprotons before 3 keV by sending them through a thin window of matter. In a second 24 hour demonstration experiment we managed to capture a few antiprotons in the small volume of the ion trap.[15] When the previous proposal was written, a dedicated beam line was being built up at CERN for our use. We were building and testing apparatus at Harvard to attach to the new beam line in Geneva when it was completed. Our team then moved to Geneva and began installing the experiment. It was an intense, exhausting and exhilarating time. I spent the entire year living in Geneva. working feverishly on the experiment as a way of obtaining my "sabbatical rest". In this year, and those that followed. four major steps forward can be easily identified.

The first step forward was a better measurement and understanding of the way that antiprotons slow while passing through matter.[16] We had done such a study in the first 24 hour demonstration experiment, but the new apparatus was far superior, we had more time, and the LEAR energy could now be lowered from 21 MeV to 6 MeV with a resulting increase in efficiency. We built a time-of-flight apparatus for this purpose and carefully compared the range of protons and antiprotons, observing a difference in their range (an example of the Barkas effect). The ranges of 6 MeV antiprotons and protons differ by about 6% in a degrader made predominantly of aluminum. These studies also demonstrated that our technique of varying the mixture of SF_6 and He gases in a cell traversed by the antiproton beam, was an effective way to tune the energy of the antiproton beam. Because of its complexity, LEAR is only able to operate at certain discrete frequencies so this energy tuning was required to obtain low energy antiproton emerging from the thin aluminum window. Also, the positron sensitive PPAC detectors we built to steer the beam into our apparatus performed perfectly even in the 6 Tesla magnetic field.

In the second major step, we captured antiprotons which were slowed below 3 keV. and then cooled them within our trap by more than 7 orders of magnitude in energy. In the greatly approved apparatus, and with more time to optimize, the number of trapped antiprotons we observed was up by orders of magnitude over that observed in the initial demonstration experiment. By colliding the energetic trapped antiprotons with a cold cloud of electrons that were preloaded in the center of the antiproton trap[17]. we were able to cool upwards of 95% of the trapped antiprotons to thermal equilibrium with the trapped electrons at 4 K. It was tremendously exciting to observe the dramatic and efficient electron cooling, which worked every bit as well as we had hoped and estimated.[18] Eventually we were able to realize more than 10^5 trapped antiprotons. cooled to

[15] G. Gabrielse. X. Fei. K. Helmerson. S.L. Rolston. R. Tjoelker and T.A. Trainor. Phys. Rev. Lett. 57. 2504, (1986).

[16] G. Gabrielse. X. Fie. L.A. Orozco, S.L. Rolston. R.L. Tjoelker. T.A. Trainor. J. Haas. H. Kalinowsky and W. Kells. Phys. Rev. A (Rapid Comm.) 40. 481 (1989).

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[18] G. Gabrielse. H. Kalinowsky and W. Kells. *Physics with Antiprotons and LEAR in the ACOL Era*. edited

thermal equilibrium at 4.2 K, with storage lifetimes exceeding 3.4 months.[19] This energy is more than 10 orders of magnitude lower than the lowest energy at which antiprotons had previously been stored. The storage time requires a vacuum better than 5×10^{-17} Torr.

Third, we demonstrated a greatly improved magnetic field stability. We carefully compared magnetic field fluctuations at the location of our antiprotons to the fluctuations of the ambient magnetic field in which the solenoid was located. For the solenoid system we had designed[20] (discussed in the previous proposal), the field fluctuations were measured to be reduced by a very large factor of 156 for spatially uniform fields.[21] Since the new solenoid system also makes a 6 Tesla magnetic field, common shielding materials such as μ-metal, iron, superconducting led balloons, etc., will not work. An important feature of the new shielding technique is that the spatial homogeneity of the magnetic field is not appreciably distorted, which is crucial for performing high accuracy mass spectroscopy experiments with antiprotons and protons. As discussed in Sec. IV.E, deducing a mass ratio from a cyclotron frequency ratio requires a stability in the magnetic field, at the accuracy desired in the mass ratio, despite the presence of unavoidable fluctuations in the ambient field. In fact, the self-shielding superconducting solenoid is a major step forward for all mass spectroscopy experiments with trapped ions, even though some groups yet find it difficult to mention this publicly.[22]

The fourth major step was that we were able to use the ultracold antiprotons, located in the highly stable magnetic field, to improve the comparison of the inertial masses of the antiproton and proton by more than a factor of 1000 over previous measurements.[23,24,25,26] Fig. 1 shows previous measurements of the antiproton to proton mass ratio on the left, and our new measurement on the right on a scale which is expanded by 1000. Inertial masses of antiproton and proton were compared and found to be the same[4] accuracy of 4×10^{-8}. This is by far the most accurate test of CPT invariance done with a baryon system. In fact, it is one of the few high precision tests of CPT invariance performed with any particle and antiparticle system. Tests of CPT invariance are summarized in Fig. 2, [27] updated based upon the compilation of the Particle Data Group.[28]

We also measured the proton to electron mass ratio and the antiproton to electron mass ratio. Initially this was done as a systematic check on our antiproton to proton comparison. We soon discovered, however, that the large trap dimensions we had chosen and our careful elimination of magnetic field in homogeneities allowed us to make the proton to electron mass ratio measurement

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by U. Gastaldi, R. Klapisch, J.M. Richard and J. Tran Thanah Van (Editions Frontières, Gif-Sur-Yvette, 1985), p. 665.

[19] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor and W. Kells, Phys. Rev. Lett. **65**, 1317 (1990).

[20] J. Tan and G. Gabrielse, J. Appl. Phys. **63**, 5143 (1988).

[21] G. Gabrielse, J. Tan, P. Clateman, L.A. Orozco, S.L. Rolston, C.H. Tseng and R.L. Tjoelker, J. Mag. Res. **91**, 564 (1991).

[22] G. Gabrielse, Phys. Rev. Lett. **64**, 2098 (1990).

[23] A. Bamberger, U. Lynen, H. Piekarz, J. Piekarz, B. Povh, H.G. Ritter, G. Backenstoss, T. Bunaciu, J. Egger, W.D. Hamilton and H. Koch, Phys. Lett. **33B**, 233 (1970).

[24] E. Hu, Y. Asano, M.Y. Chen, S.C. Cheng, G. Dugan, L. Lidofsky, W. Patton, C.S. Wu, V. Hughes and D. Lu, Nucl. Phys. **A254**, 403 (1975).

[25] P. Roberson, T. King, R. Kunselman, J. Miller, R.J. Powers, P.D. Barnes, R.A. Eisenstein, R.B. Sutton, W.C. Lam, C.R. Cox, M. Eckhause, J.R. Kane, A.M. Rushton, W.F. Vulcan and R.E. Welsh, Phys. Rev. C **16**, 1945 (1977).

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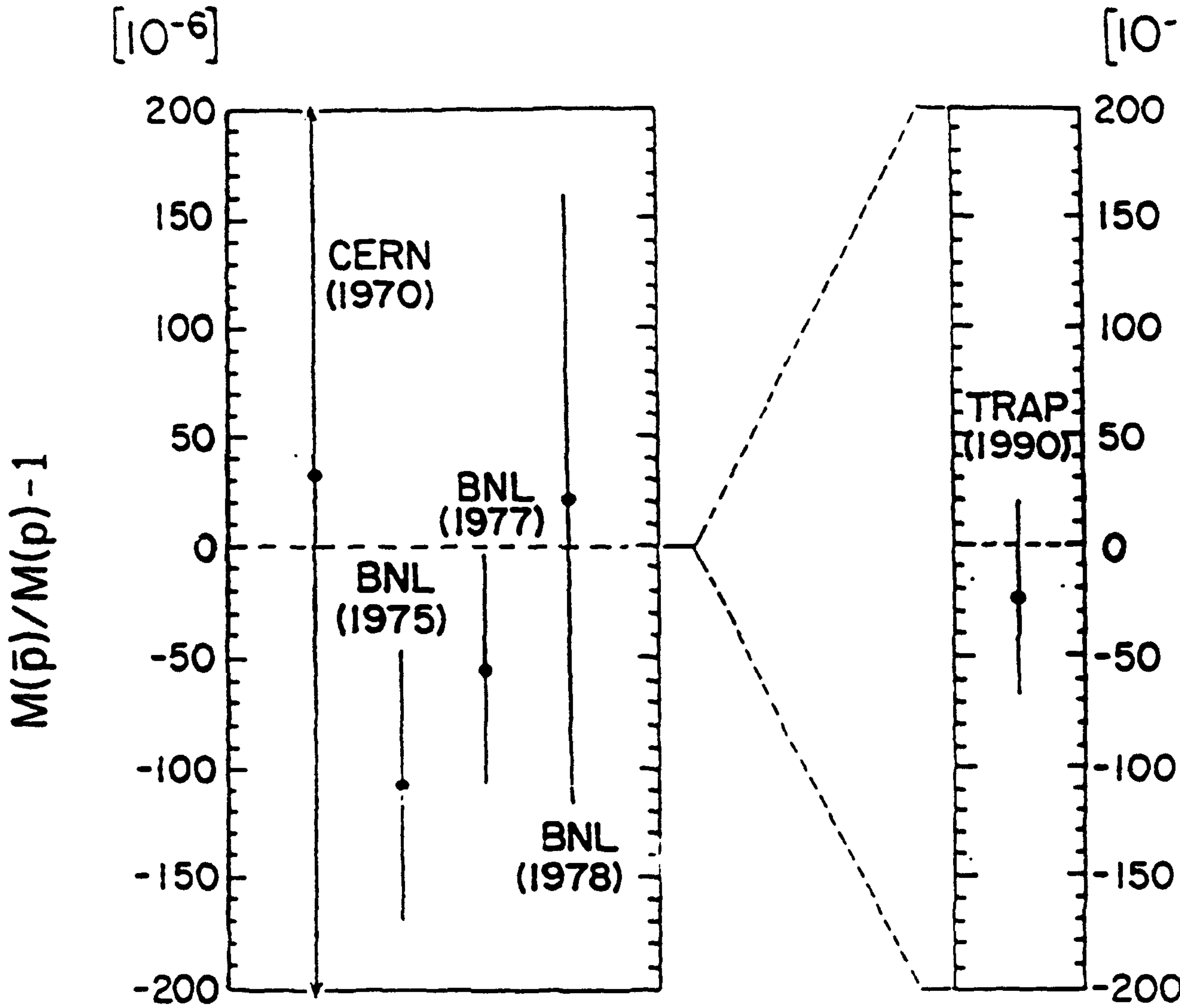

Figure 1: Measurements of the ratio of antiproton to proton masses (Refs. 23-26). The new measurement on the right-hand side is on a scale expanded by 1000.

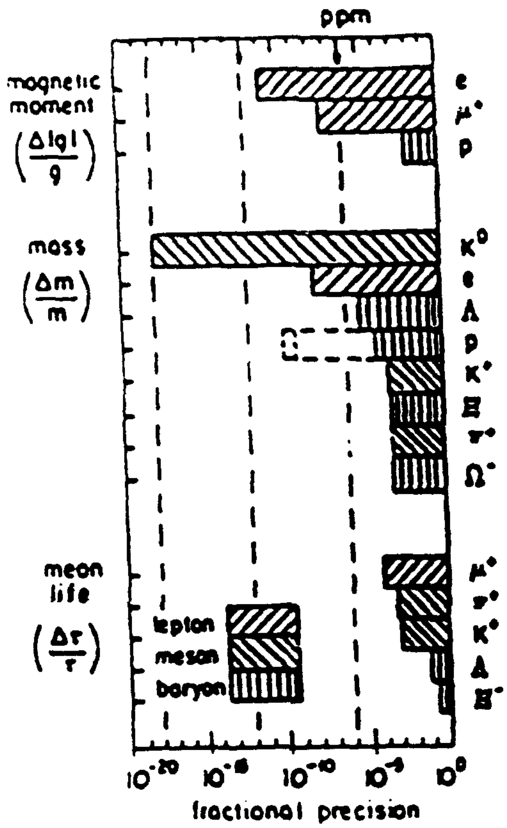

Figure 2: Invariance under CPT transformations implies that a particle and its antiprotons will have the same magnetic moment (except for opposite sign), the same inertial mass and the same mean life. The above tests of CPT invariance are discussed on p. 37.

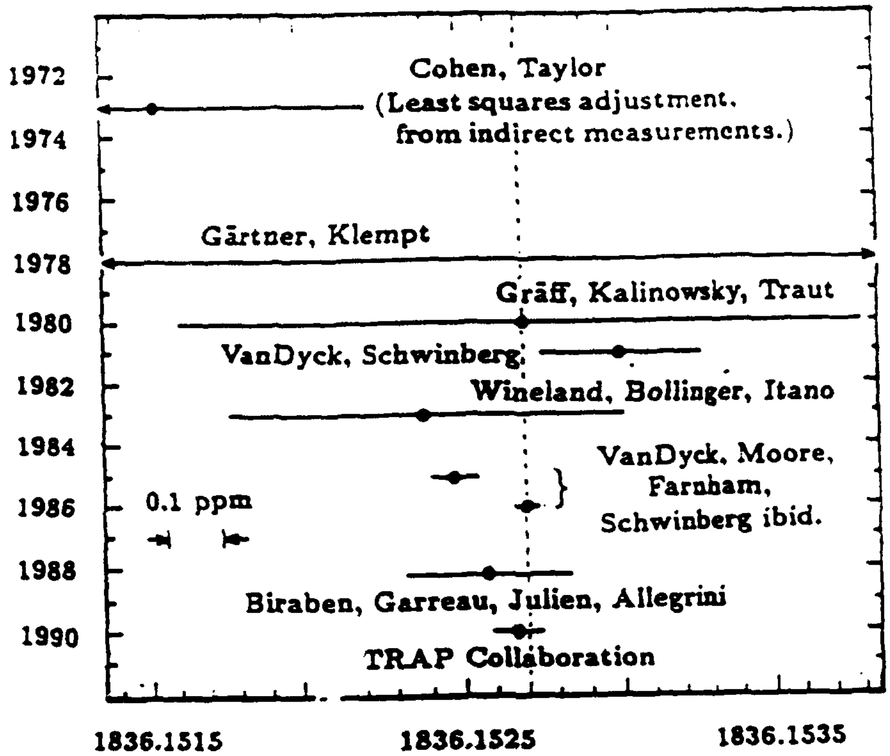

Figure 3: Measurements of the ratio of proton and electron masses. Our new measurement is the lower point.

with roughly the same accuracy as the previous best measurement. Fig. 3 shows a series of proton to electron mass ratios with error bars steadily decreasing as a function of time. The new ratio which we have published (the lower point in the figure) have error bars slightly larger than the two most recent values reported by Van Dyck, et. al.[29,30] We agree with the corrected ratio[28] and disagree with the earlier measurement[27] which had a systematic problem. Though not yet published, we now have error bars comparable to those given by Van Dyck, et.al.

The progress summarized above is elaborated in the Project Description (Sec. IV). The four techniques developed and demonstrated are now being used and refined in the pursuit of even much higher accuracy comparisons of the inertial masses of the antiproton and proton.

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L.S. Brown, G. Gabrielse, J. Tan, K.C.D. Chan;
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G. Gabrielse, L. Haarsma, S. Rolston and W. Kells;
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3. "Self-shielding Superconducting Solenoid Systems",
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4. "First Capture on Antiprotons in an Ion Trap: Progress Toward a Precision Mass Measurement and Antihydrogen",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas and W. Kells;
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Hyper. Int. **44**, 349 (1988).
8. "Tests of CPT Invariance with Leptons and Baryons",
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Nucl. Phys. B**8**, 448 (1989).
9. "Open-ended Penning Traps for High Precision Experiments",
G. Gabrielse, L. Haarsma, S.L. Rolston;
Intl. J. of Mass Spec. and Ion Proc. **88**, 319 (1989).
10. "Barkas Effect with Antiprotons and Protons",
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G. Gabrielse and B. Brown;
in *The Hydrogen Atom*, Edited by G.F. Bassani, M. Inguscio, T.W. Hansch, (Springer-Verlag, Berlin, 1989).
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15. "A Superconducting Solenoid System Which Cancels Fluctuations in the Ambient Magnetic Field", G. Gabrielse, J. Tan, P. Clateman, L.A. Orozco, S.L. Rolston, C.H. Tseng and R.L. Tjoelker; J. of Mag. Res. **91**, 564 (1991).
16. "Synchronization of Parametrically Pumped Electron Oscillators with Phase Bistability", J. Tan, G. Gabrielse; Phys. Rev. Lett. **67**, 3090 (1991).
17. "Cooling Antiprotons and Positrons", G. Gabrielse; in *Proc. of the International School of Physics, Enrico Fermi*, Varenna, Italy (1991).
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28. "Extremely Cold Antiprotons for Antihydrogen Production"
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Hyperfine Interactions *76*, 81 (1993).
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C. Tseng and G. Gabrielse
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30. "Extremely Cold Positrons for Antihydrogen Production"
L. Haarsma, K. Abdullah, G. Gabrielse
Hyperfine Interactions *76*, 143 (1993).
31. "Observing a Single Trapped Antiproton"
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Nuclear Physics A *558*, 701c (1993).
32. "A Single Trapped Antiproton and Antiprotons for Antihydrogen Production
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in Proceedings of Workshop on Traps for Antimatter and Radioactive Nuclei (TRIUMF), Vancouver, British Columbia, Canada (in press).

C. Colloquia and Invited Talks Acknowledging AFOSR Support

1988

Feb. 2	Calvin College (physics colloquium)
Feb. 3	Notre Dame (physics colloquium)
Feb. 4	University of Chicago (physics colloquium)
Feb. 25	Amherst College (physics colloquium)
Feb. 26	University of Connecticut (physics colloquium)
Apr. 7	Pennsylvania State University (physics colloquium)
May 16	Third Conference on the Interaction Between Particle and Nuclear Physics, Rockport, Maine (invited plenary lecture)
July 1	Symposium on the Hydrogen Atom at the Scuola, Normale Superiore, Pisa, Italy (invited lecture)
Sept. 6	IX European Symposium on Antiproton-Proton Interactions and Fundamental Symmetries, Mainz, Germany (invited lecture)

1989

Jan. 10	College de France and Ecole Normale Superieure, Paris, France (invited lecture)
Feb. 15	University of Aarhus, Aarhus, Denmark (physics colloquium)
Feb. 23	California Institute of Technology (physics colloquium)
Feb. 28	University of California at San Diego (physics colloquium)
Mar.2-4	First Annual Symposium on Frontiers of Science sponsored by the National Academy of Sciences (invited participant)
May 1	American Physical Society, Baltimore, Maryland (invited speaker)
June 9	University of Karlsruhe, West Berlin, Germany (physics colloquium)
July 10	Combined Colloquium of the Technical University of Munich, the Maximillian University and the Max Planck Institute for Quantum Opics, Munich, West Germany
Aug. 23	Institute de Lau Langevin, Grenoble, France (physics colloquium)
Sept 12	IBM Research Laboratory, Yorktown, New York (physics colloquium)
Sept 22	University of Wisconsin at Madison (physics colloquium)
Sept 28	Princeton University (physics colloquium)
Oct. 2	Harvard University (physics colloquium)
Oct. 20	University of Virginia, Charlottesville (physics colloquium)
Nov. 6	27th Annual New Horizons of Science Briefing of the Council for the Advancement of Science Writing at Cornell University (invited lecture)

1990

Jan. 12	Argonne National Laboratory, Chicago, Illinois (physics colloquium)
Jan. 24	University of Pennsylvania (physics colloquium)
Apr. 16	Washington D.C. Meeting of the American Physical Society (invited lecture)
Apr. 30	Rutherford Laboratory, Oxford, England (physics colloquium)
May 1	High Energy Physics Seminar, Oxford University, Oxford, England
May 23	Meeting of the Division of Electron, Atomic, Molecular and Optical Physics, Monterey, California (invited lecture)
July 4	Low Energy Antiproton Physics Conference, Stockholm, Sweden (invited lecture)
Aug. 3	International Conference of Atomic Physics, Ann Arbor, Michigan (invited lecture)
Aug. 15	Gordon Conference on Few Body Physics, New Hampshire (invited lecture)
Sept 25	MIT (atomic physics colloquium)
Sept 26	Boston University (physics colloquium)
Sept 27	Los Alamos National Laboratory (physics colloquium)
Oct. 18	University of Chicago (physics colloquium)
Oct. 24	Division of Nuclear Physics Fall Meeting, University of Illinois at Urbana (invited lecture)
Nov. 6	Optical Society of American, Boston, Massachusetts (invited lecture)
Nov. 10	Society of Physics Students Zone Meeting, Rolla, Missouri, (keynote speaker)
Dec. 6	New York University (physics colloquium)

1991

Jan. 18	New York Academy of Science (featured speaker)
Jan. 23	Rice University (physics colloquium)
Feb. 13	University of Massachusetts at Amherst (physics colloquium)
Feb. 25	Cornell University (physics colloquium)
Mar. 21	Princeton University (plasma physics colloquium)
Apr. 1	Brown University (physics colloquium)
May 3	Yale University (physics colloquium)
July 4	Gordon Conference on Few Body Physics, New Hampshire (invited lecture)
July 12	Italian Physical Society Summer School, International School of Physics Varenna, Italy (invited lecture)
Aug. 26	9th International Conference on Positron Annihilation, Szombatheley, Hungary (invited lecture)
Oct. 11	Fermi National Accelerator Laboratory (physics colloquium)
Oct. 23	University of Rochester (physics colloquium)
Oct. 28	Haverford College (physics colloquium)
Nov. 7	Massachusetts Institute of Technology (physics colloquium)

1992

Feb. 25	York University (Toronto), (physics colloquium)
July 30	Antihydrogen Workshop (Munich, Germany) (invited lecture)
Aug. 4	13th International Conference on Atomic Physics (Munich, Germany) (invited lecture)
Aug. 10	CERN Summer Student Lecture Program (invited lecture)
Sept. 19	Second Biennial Conference on Low-Energy Antiproton Physics - LEAP '92 (Courmayeur, Italy) (invited lecture)
Oct. 26	Coast Guard Academy, New London, CT (physics colloquium)
Nov. 3	National Science Foundation, The George Washington University (joint physics colloquium)
Nov. 24	University of Tennessee, Knoxville (physics colloquium)

1993

Feb. 11	American Association for the Advancement of Science, Public Science Day, Cambridge Rindge and Latin School (invited lectures)
Feb. 12	American Association for the Advancement of Science, Boston (invited lecture)
Feb. 17	University of Delaware (physics colloquium)
Mar. 12	McGill University (Montreal), (physics colloquium) (invited lecture)
Feb. 25	Workshop on Traps for Antimatter and Radioactive Nuclei (TRIUMF), University of British Columbia, Vancouver (invited lecture)
Mar. 12	McGill University, Montreal (physics colloquium)
Mar. 25	Society of Physics Students, Worcester Polytechnic Institute (invited lecture)
Apr. 13	Washington D.C. Meeting of the American Physical Society (undergraduate address)
Apr. 14	Washington D.C. Meeting of the American Physical Society (invited lecture)
Apr. 20	Brookhaven National Laboratory (physics colloquium)
May 4	Quantum Electronics Laser Science Conference, Baltimore (invited lecture)
May 17	Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society (Reno, NV) (invited lecture)
June 3	California Institute of Technology (physics colloquium)
June 15	GSI (Darmstadt, Germany) (physics colloquium)
June 22	University of Bern, Switzerland (physics colloquium)
June 23	University of Geneva, Switzerland (physics colloquium)
July 5	Gordon Conference (New Hampshire) (invited lecture)
July 16	Positron Satellite Meeting to ICPEAC, Bielefeld, Germany (invited lecture)
Sept. 15	2nd Workshop on Nucleon-Antinucleon Physics (NAN '93), Institute of Theoretical Physics, Moscow