Trapping Low Energy Antiprotons in an Ion Trap

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by

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Abstract

A fraction of antiprotons from the Low Energy Antiproton Ring (LEAR) of CERN are slowed from 5.9 MeV to below 3 keV as they pass through thin foils. Transmitted particle energy distribution and low energy antiproton yield are measured by a time-of-flight technique. The difference in the range of protons and antiprotons (known as the Barkas effect) is observed. While still in flight, up to 1.3×10^5 antiprotons with energies between 0 eV to 3 keV are stored in an ion trap from a single pulse of 5.9 MeV antiprotons leaving LEAR, thus a trapping efficiency exceeding of 4×10^{-4} is established. Trapped antiprotons maintain their initial energy distribution unless allowed to collide with a cloud of trapped electrons, whereupon they slow and cool below 1 meV in 10 s, and fall into a harmonic potential well suited for precision mass measurements. The slowing, trapping and cooling of antiprotons are the main focus of this thesis. The stored antiprotons are in thermal equilibrium at 4.2 K. In this ion trap, the antiproton cyclotron frequency is measured and compared with the proton (or electron) cyclotron frequency. Our new measured ratio of the antiproton and proton inertial masses, with its 4×10^{-8} uncertainty, is more than three orders of magnitude more accurate than previous measurements using exotic atoms. This is the most precise test of CPT invariance with baryons. The antiproton lifetime in an ion trap was measured to be more than 103 days by trapping a cloud of antiprotons for 59 days. This indicates the number density of atoms is less than $100/cm^3$ which corresponds to the pressure in the vacuum chamber being less than 5×10^{-17} Torr at 4.2 K if we apply the ideal gas law.

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Papers published by the author during his Ph.D. study

1. *First capture of antiprotons in a Penning trap: a kiloelectronvolt source.*
   G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells,
   Phys. Rev. Lett. **57**, 2504 (1986).

2. *High-voltage switching for in-flight capture of keV antiprotons in a Penning trap.*
   X. Fei, R. Davisson, and G. Gabrielse,
   Rev. Sci. Instrum. **58**, 2197 (1987).

3. *Barkas effect observed with antiprotons and protons.*
   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**40**, 481 (1989).

4. *Cooling and slowing of trapped antiprotons below 100 meV.*
   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).

5. *Thousandfold improvement in the measured antiproton mass.*
   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).

6. *Prospects for experiments with trapped antiprotons.*
G. Gabrielse, K. Helmerson, R. Tjoelker, X. Fei, T.A. Trainor, W. Kells, and H. Kalinowsky,
in **Proceedings of the first workshop on antimatter physics at low energy**, ed. by B.E. Bonner, L.S. Pinsky (Fermilab, Batavia, 1986), p.211.

7. *First antiprotons in an ion trap.*
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells,
in **Laser Spectroscopy VIII**, ed. by W. Persson and S. Svanberg, (Springer-Verlag, New York, 1987), p.22.

8. *First capture of antiprotons in an ion trap: progress toward a precision mass measurement and antihydrogen.*
G. Gabrielse, X. Fei, L. Haarsma, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells,
Physica Scripta, **T22**, 36 (1988).

9. *Cryogenic antiprotons: a 1000-fold improvement in their measured mass.*
G. Gabrielse, X. Fei, W. Jhe, L.A. Orozco, J. Tan, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, and W. Kells,
in **Atomic Physics XII**. (1990).

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