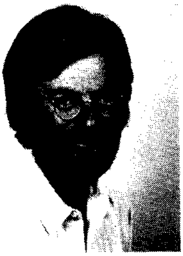
A MEASUREMENT OF THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON

Michael H. Holzscheiter
Los Alamos National Laboratory
Physics Division
Los Alamos, NM 87545 U.S.A.



ABSTRACT

A fundamental experiment in gravity proposed by us, is the measurement of the gravitational force on antimatter. This measurement would constitute the first direct test of the Weak Equivalence Principle (*WEP*) for antimatter. The availability of low-energy antiprotons at CERN has made such an experiment feasible, and a proposal to carry out such a measurement has been accepted by the CERN Program Committee.

We plan to use a time-of-flight technique similar to that pioneered by Fairbank and Witteborn in their measurement of the gravitational force on an electron. Very slow particles are launched into a vertical drift tube and the time-of-flight spectrum of these particles is recorded. This spectrum will exhibit a cut-off point directly related to the gravitational acceleration of the particles. Obtaining very slow antiprotons involves several stages of deceleration. Antiprotons from LEAR will be initially decelerated from 2 MeV to tens of kilovolts by passing them through a thin foil. After capture and cooling in a series of ion traps, the antiprotons will be in a thermal distribution with a temperature of a few degrees Kelvin. These ultra-cold antiprotons will then be released a few at a time into the drift tube. A detector will measure the arrival time of the particles at the exit of the drift tube. H^--ion, which have almost identical electromagnetic properties to the antiprotons, will be used for comparison and as a calibration standard.

About 375 years ago, Galileo Galilei reportedly performed a well-known experiment in the history of physics. He dropped weights of wood and lead from a "high tower" in Pisa to determine their relative rate of fall. From this and other experiments, Galileo concluded that objects with different *compositions* and/or *masses* fall with the same acceleration in the Earth's gravitational field.[1)]

Between 1889 and 1908, Eötvös[2)] confirmed Galileo's results with a precision of 5 parts in 10^9 for a variety of materials in the Earth's gravitational field. Then twenty-five years ago, Dicke[3)] achieved a precision of 5 parts in 10^{12} for the universality of free-fall of objects towards the Sun. Galileo's conclusion is now considered to be a principle of physics - the Weak Equivalence Principle.

Almost all modern attempts to construct consistent quantum-field theories of gravity introduce weak-equivalence-principle-violating interactions and non-newtonian contributions to gravity. To test these challenges, we propose to perform a new version of Galileo's experiment, in which the gravitational acceleration of antimatter towards the Earth is compared with that of ordinary matter. Specifically, we intend to measure the gravitational mass of the antiproton, relative to the H^- ion.

To measure the gravitational mass of the antiproton, the antiproton energy must be low enough for the gravitational effect to be measurable, of order 10^{-7} eV or 1.2 mK. The lowest-energy antiproton beam currently available is at the LEAR Facility at CERN (*2 MeV*). To perform the measurement, this energy has to be reduced by about thirteen orders of magnitude.

The experimental sequence starts with the bunching of the 2 MeV beam in the LEAR ring. A single-phase bucket containing $\sim 10^8$ particles is fast extracted from LEAR and delivered to the experiment. The first major step in reduction of energy will be accomplished by passing the antiprotons through a thin foil. Test measurements[4)] have shown that up to 17% of the particles may emerge from the foil if the thickness is chosen correctly. Those particles will then be caught in a long, cylindrical, electromagnetic trap with 50 kV well depth and 50-cm length.

After the antiprotons have been cooled to approximately 1 eV, using electron cooling[5], they will be ejected and transferred to a small ion trap where resistive cooling is used to reduce the energy further to an ~ 4k thermal distribution.

At this time, the particles will be released a few at a time vertically into a 1-meter drift tube used to shield the particle orbits from stray-electric fields. The particle time-of-flight spectrum through the drift tube is then measured. This spectrum, reflecting the initial distribution of velocities, will exhibit a cut-off corresponding to the equality of the initial kinetic energy and the gravitational potential energy change in the drift tube. This cutoff time is related to the gravitational acceleration, g, experienced by the particle by $t_c = \sqrt{2L/g}$, where L is the drift length.

A schematic of the set-up of the entire experiment is shown in Figure 1. For test purposes, we have separated the development into the horizontal part (*capture and cooling*) and the actual gravity experiment (*vertical part*).

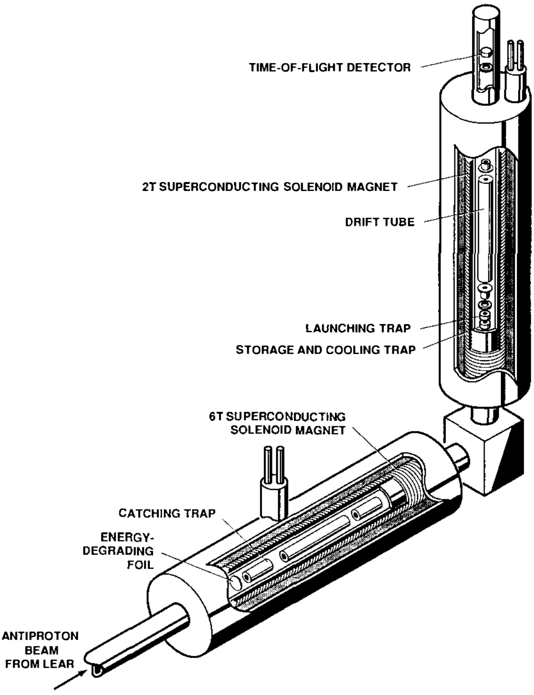


Fig. 1. Artist's conception of antiproton gravity experiment.

To this time we have successfully characterized the degrading of antiprotons in thin foils and established that the theoretical predictions given by the TRIM computer code6) are correct to within 10%. This allows us to confidently predict to capture 10^7 or more antiprotons into the initial trap. In an independent experiment, we have captured protons and negative hydrogen ions from a low-energy ion source into an elongated Penning trap.7) More recently, we have constructed a beam line combining the degrading and capture into one experiment. Here we have studied the degrading of 2-5 MeV protons by a thin foil mounted at the entrance electrode of the 50-kV trap inside the 6-Tesla magnetic field and verified the earlier measurements at LEAR. The size of the trap is laid out so the fast (*50 keV*) particles from the beginning of a 250-ns pulse have not been reflected from the exit electrode and returned to the foil by the time the last particles emerge from the foil. At this moment, the potential of the foil will be quickly (*100 ns*) raised to 50 kV, trapping all particles below 50 keV. In the case of antiprotons, electrons can be stored in the same potential well. Synchrotron radiation in the strong magnetic field will cool these electrons with a time constant of 300 msec (*in 6T*) and they will in turn cool the antiprotons by Coulomb interaction. This method can not be demonstrated with protons because of the opposite electric charge, but electron cooling has been shown by G. Gabrielse5) to be very efficient, and extrapolating his results to our specific set-up gives a total cooling time from 50 keV to 1 eV of approximately 100 seconds. This requires a minimum storage time for the antiprotons of several hundred seconds, requiring a vacuum of 10^{-13} Torr or better. This may only be possible by immersing the entire apparatus into liquid helium, an option which we have available with the design of our horizontal magnet dewar.

The single largest challenge in the actual gravity measurement is the shielding of all stray-electric fields to a level well-below $10^{-7}\ {}^{V}/_{m}$. Even if the entire drift region is being surrounded by a conducting cylinder, (*the drift tube*), the local variations of the work function on the inside surface of this cylinder will produce electric fields on axis, which could be overwhelming the effects of gravity.

Therefore, we have built a vibrating probe apparatus (*Kelvin probe*) to study surface potentials on small samples of different materials. We have succeeded in identifying candidates for the drift-tube surface, but the sensitivity of these measurements is limited to a field 100 times stronger than ultimately needed. To improve upon these results, we will have to use gravity itself as a probe. Therefore, we are constructing a test experiment where different mass ions from an ion source will be launched into a half-scale model of our final drift tube. The same detector arrangement as in the final experiment will be used at the exit side of the tube to detect these ions and to study the time-of-flight distribution. Detecting ions moving under the influence of gravity will constitute the ultimate test of having achieved sufficient shielding of stray-electric fields.

Once the drift-tube has been tested, we will replace the ion source with a Penning trap and use the drift-tube as a tool to analyze the launching of ultra-low energy particles from the trap.

After measuring *g* for protons and negative hydrogen ions at Los Alamos, the gravity apparatus will be shipped to CERN. There it will be coupled to the catching device in order to measure the gravitational acceleration of antiprotons and thereby perform the first test ever of the weak equivalent principle for antimatter.

Acknowledgements

I am indebted to all members of the PS 200 collaboration for work presented in this paper. Current members include R. E. Brown, J. Camp, T. Darling, P. Dyer, T. Goldman, D. B. Holtkamp, R. J. Hughes, N. Jarmie, N. S. P. King, D. C. Lizon, R. Martinez, M. M. Nieto, and C. Webb (Los Alamos National Laboratory), F. C. Witteborn (NASA/Ames Research Center), S. Cornford, R. A. Kenefick, K. Hosea (Texas A & M University), D. Oakley, and R. Ristinen (University of Colorado/Boulder).

References

1) Galileo Galilei, "Dialogues Concerning Two New Sciences," (1638), Dover Translation 1914.

2) R. V. Eötvös, D. Pekar, E. Tekete, Ann. Phys. (Leipzig) 68, 11 (1922).

3) P. G. Roll, R. Krotkov, R. H. Dicke, Ann. Phys. (New York) 26, 442 (1967).

4) N. Hill, D. B. Holtkamp, N. S. P. King, to be published.

5) G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelkes, J. Haas, H. Kalinowsky, T. A. Trainor, W. Kells, Phys. Rev. Lett. 63, 1360 (1989).

6) J. F. Ziegler, J. P. Biersack, U. Littmark, ''The Stopping Range of Ions in Solids,'' Pergamon Press (1985).

7) M. H. Holzscheiter, R. E. Brown, N. Jarmie, D. C. Lizon, Physica Scripta, T22, 290 (1988).