LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR--88-3193

TI89 000313

TITLE FALLING ANTIMATTER: AN EXPERIMENT TO MEASURE THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON

AUTHOR(S) P. Dyer, J. Camp, M. H. Holzschelter, S. Graessle

SUBMITTED TO Tenth International Conference on the Application of Accelerators in Research and Industry, Denton, Texas

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report contains information which may be subject to copyright. The United States Government retains a nonexclusive, irrevocable, and exclusive license in this report for the purpose of reproducing, reprints, and distributing it for Governmental purposes, not withstanding any copyright notation that may appear hereon.

This report is prepared as an account of work performed under the auspices of the U.S. Department of Energy.

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MAILED

**FALLING ANTIMATTER: AN EXPERIMENT TO MEASURE THE GRAVITATIONAL
ACCELERATION OF THE ANTIPROTON**

P. DYER, J. CAMP and M. H. HOLZSCHEITER

*Physics Division, Los Alamos National Laboratory, Los Alamos, NM 87545,
USA*

S. GRAESSLE

Department of Physics, Rice University, Houston, TX 77251, USA

Abstract

According to some theories of gravity, antimatter will fall faster than matter in the earth's gravitational field. An experiment to measure the gravitational force on the antiproton is under construction. Antiprotons of a few MeV from the LEAR facility of CERN will be slowed down and caught in a large Penning electromagnetic trap. They will then be cooled and transferred to Penning cooling and launching traps. The gravitational acceleration will be measured by time-of-flight in a drift tube shielding stray electric fields, and will be compared with that measured for H^+ ions. Progress on a number of fronts is described.

1. Introduction

Measuring the motion of an antiparticle in the earth's gravitational field is an experiment that has never been done. Such an experiment has become increasingly of interest with the recent controversial evidence for new composition-dependent forces of gravitational strength [1] or for deviations from the inverse square law [2]. Furthermore, many theories, attempting to unify quantum mechanics and gravity, introduce graviscalar and gravivector partners of the original graviton. Could the new forces be manifestations of additional terms in the gravitational interaction? An antimatter-matter measurement is of special interest because the vector term would change sign from that of a matter-matter experiment. An antiproton could fall significantly faster in the earth's field than a proton [3].

2. Outline of the experimental configuration

The gravitational force on a charged particle of known initial velocity may be measured by releasing it at the bottom of a vertical, field-free drift tube and measuring the time it takes to travel to a detector at the top. For the case of a large number of particles that have a continuous vertical velocity distribution, the gravitational force is measured by the cutoff in the time-of-flight distribution, as particles with very low velocities reverse direction and do not reach the detector. The potential energy difference for an antiproton over a 1 meter vertical path is only of order 10^{-7} eV, so the effect of gravity is appreciable only for particles having a kinetic energy not much larger than this. Effects of stray electric fields and magnetic field gradients in the drift tube must be kept at this level or below

Antiprotons created in high-energy collisions have kinetic energies of a few GeV. We are thus faced with the problem of decelerating them by 16 orders of magnitude. Along the way the antimatter must not be allowed to interact with enough matter to annihilate it. The lower the energy, the higher the annihilation cross section, so the very low-energy part of the apparatus must be maintained at extremely high vacuum.

A schematic diagram of a possible experimental configuration is shown in fig. 1. The first three orders of magnitude of energy reduction are achieved by the CERN LEAR (Low Energy Antiproton Ring) facility. The energy of the antiprotons will be 2 MeV. About 10^8 antiprotons can be ejected in a 200 ns long bunch with the fast extraction mode. A further degrading of the energy to 50 keV and below will be accomplished by slowing the antiprotons in a solid or gas. The antiprotons will then be caught in a large Penning trap (axial confinement by an electrostatic field and radial confinement by a magnetic field). There they will be cooled to 10 eV or below. The particles will be transferred from this trap to the first of two small quadrupole Penning traps operated at cryogenic temperatures and very high vacuum, where they will be resistively cooled to less than 10^{-3} eV. The first trap will confine about 10^6 antiprotons. One hundred at a time (to minimize Coulomb repulsion in the drift tube) will be transferred to the second small trap, re-cooled, and then launched into the drift tube. The time-of-flight distribution of the particles reaching the detector at the top of the drift tube will be measured (Alternatively, the antiprotons could be dropped downward to a detector). This detector will be a micro-channel plate or a cryogenic

calorimeter. To eliminate systematic errors, H^- ions will be launched into the drift tube under the same conditions. It will be possible to compare antiproton and H^- cutoffs in the time-of-flight distributions to deduce the gravitational force on antimatter, relative to matter.

In the following sections, details of design considerations for this experiment (PS 200) [4] are given. Tests of the various parts of the experiment now underway are described.

3. Initial energy degrading

For capturing the antiprotons ejected from LEAR into a Penning trap, their energy first has to be reduced to about 50 keV or less. Two options have been proposed for this degrading process. The first is simply to put a solid foil in front of the large catching trap. As low-energy stopping powers have not been measured for antiprotons, best estimates are obtained from calculations with an energy-loss and multiple scattering code modified for negative particles. Energy-loss data for μ^- , π^- , and Σ^- particles can be used to test the code. It is anticipated that 5 to 10% of the antiprotons in a burst can be degraded into an energy window that can be trapped. Time is scheduled at LEAR in the fall of 1988 to measure degraded energies of 6-MeV protons and antiprotons. Data from this experiment will be used to test the code critically.

The second option (termed the "cyclotron trap") is considerably more complex, but has the potential for delivering more antiprotons with a smaller energy range. This option is to inject the energetic

antiprotons into a gas-filled weak-focusing magnetic field, where they would spiral into the center as they lose energy. On reaching energies of the order of 10 keV, they would be extracted along the axis and injected into the catching trap. Such a system has been used for other LEAR experiments, where the antiprotons remained inside the magnet [5]. Preliminary modeling calculations indicate that an electrostatic extraction system would be very efficient.

4. Ion traps and cooling

Following the initial energy degrading, antiprotons will be trapped in a multi-ring Penning trap. The maximum energy and width in time of the antiproton beam burst dictate a 50-keV trap of length 0.5 m (for the foil degrading case). To limit the number of antiprotons annihilated, the pressure must be held below 10^{-12} torr. To admit the antiprotons, the entrance potential will be dropped until the burst has entered and will then be quickly raised to 50 keV before the antiprotons have been repelled from the trap by the potential at the exit end. Following cooling, the exit potential will be dropped, and the antiprotons will be transferred to the first small quadrupole trap.

In a first experimental test, externally injected negative hydrogen ions up to 10 keV were captured in a quadrupole Penning ion trap of axial length 1.5 cm [6]. More recently, a burst of 10-keV protons was captured in a 12 kV multi-ring trap of total length 15 cm. This trap, mounted inside a superconducting solenoid of 6 T field, consists of 15 circular electrodes biased at the appropriate voltages to provide a harmonic potential along its axis. The pressure in the trap

is about 10^{-11} torr. The entrance electrode high voltage is dropped for a microsecond to admit protons, then brought back up with a 100-ns risetime. After a variable delay, the exit voltage is slowly dropped, and the expelled protons are detected by a micro-channel plate. The time of release is a measurement of the energy of the particle in the trap (given knowledge of the exit-electrode barrier as a function of time). A time-of-release spectrum is shown in fig. 2. Lifetimes of the protons in the trap are measured by varying the storage time, and are a few seconds at the present trap pressure. Radiofrequency excitation of the axial degree of freedom has been used to identify the ion species trapped. Studies at higher beam energies and trap voltages are in progress.

The next-generation test of trapping will be performed with 2-MeV protons from a Van de Graaff accelerator injected through a foil degrader into a 0.5-m long multi-ring trap. The superconducting magnet for these tests has arrived. This magnet has a room-temperature bore, but can be converted to a cold bore if necessary for vacuum considerations. The room-temperature design goal is 10^{-12} torr; hydrogen leakage through the stainless steel walls will be reduced by vacuum heat treatment before assembly. The beam line and trap are presently under construction.

Commonly-used resistive cooling is too slow for the large catching trap. Two alternative techniques are under consideration for the reduction of energy from 50 keV to less than 10 eV.

The first is stochastic cooling [7]. In a harmonic trap all particles oscillate at the same frequency independent of amplitude (and thus energy). Due to the finite bandwidth of the system, the particle motion will quickly randomize, leaving a net center-of-mass motion due to statistical imbalance. Signals induced on the electrodes from this center-of-mass motion can be amplified, delayed, and fed back to the electrodes to generate an electric field opposing the motion. The correction can be optimized to completely stop the center-of-mass motion and thus reduce the kinetic energy of the ensemble of particles. Repeated cycles will cool the particles to a limit given by the noise temperature of the external circuitry. Such cooling has recently been demonstrated for protons in a small quadrupole trap [8]. This work will continue with a multi-ring trap.

The second technique under consideration for the catching trap is electron cooling. Electrons in a Penning trap will rapidly cool to the ambient temperature via synchrotron radiation. If a large number of electrons can be stored in the trap along with the antiprotons (enough electrons to reduce heating of the electrons by the antiprotons), the antiprotons will be cooled by collisions. Cooling times for antiprotons less than 100 seconds are theoretically feasible. (A harmonic trap is not required.) However, testing electron cooling without using antimatter is difficult. If electrons are trapped along with H^- ions, the electrons will detach the H^- electrons before collisions will cool the ions significantly, for ion energies above about 2 keV. A test we are initiating is to cool negative oxygen ions with electrons. Here the

electron detachment energy is higher, so cooling should be observable up to about 50 keV.

Following cooling in the large catching trap, the antiprotons will be released, accelerated to about 1 keV, transferred around a 90° bend, decelerated, and captured in the first of a set of two cryogenic quadrupole ion traps, where they will be cooled to 4 K (3×10^{-4} eV). Since the trap dimensions will be small, resistive cooling will be adequate in these traps. As many as 10^6 antiprotons from each LEAR burst may be caught in the first small ion trap. However, if all of these were launched into the drift tube at once, their mutual Coulomb repulsion would overwhelm the effect of gravity. Computer simulations have shown that the repulsion effects become tolerable only when less than 100 particles at a time are launched. It is thus necessary to transfer this number of antiprotons from the first into the second small trap, re-cool, and then launch them into the drift tube. Such a bunch can be launched about once every second. A prototype of the first small ion trap is being tested.

5. Drift tube

To measure the gravitational force on the antiproton by time-of-flight, it is necessary to have the particles drift under the influence of gravity for about a meter, in conditions where the stray electric field is less than 10^{-7} volts per meter. The inside of a cylindrical conducting tube can provide such an environment if it does not itself produce electric fields of the above magnitude. Furthermore, the 2 T magnetic field inside the drift tube (required to keep the antiprotons

on axis) must be homogeneous to one part in 10^5 to keep the magnetic gradient force well below the gravitational force. There are many systematic errors that can arise in the gravity measurement. One that is of great concern is electric fields from the patch effect. A normal metallic surface is composed of many small crystalline patches, each having a slightly different work function, and thus each at a slightly different electric potential. In the work of Lockhart et al. [9], it was reported that electric fields in a drift tube decreased dramatically below 4.5 K. As this subject is controversial and certainly not well understood, we are attempting our own measurements of patch effects for several different surface choices. A single-crystal drift tube would not exhibit a patch effect, but would be exceedingly difficult to construct. The present plan is to investigate amorphous conductive surfaces (no crystalline patches) deposited on the inside of a metal tube. Possibilities under consideration are nickel-phosphorous, carbon, and amorphous silicon doped to increase the conductivity. Surface temperatures, both during coating and during later baking in vacuum must be considered. Measurements of patch-effect fields from small samples as a function of temperature are being initiated with a Kelvin probe.

The most stringent tests will be made with a half-scale cryogenic test-stand complete with ion source, superconducting solenoid magnet, drift tube, and detector. Here the time-of-flight of ions in a gravitational field will be measured, beginning with heavy ions and working down to hydrogen. In a later stage, the ion source will be replaced by a quadrupole Penning trap. The high-homogeneity

superconducting magnet and the cryogenic vacuum system are under construction.

6. Conclusion

A time-of-flight experiment to measure the gravitational force on the antiproton is under development. Trapping of externally-generated particles in a multi-ring Penning trap has been studied, stochastic cooling has been demonstrated in a quadrupole Penning trap, and drift tube studies are beginning. In the final experiment, systematic errors will be reduced by making the same measurement for H^- ions. The design goal is to make a 1% measurement.

We are indebted to other members of the PS 200 experimental collaboration for work presented here. Current members include R. E. Brown, D. B. Holtkamp, N. Jarmie, N. S. P. King, D. Lizon, R. Martinez, C. Webb (Los Alamos National Laboratory), F. C. Witteborn (NASA/Ames Research Center), N. Beverini, S. Mango, R. Roggiani, G. Torelli (University of Pisa), V. Lagomarsino, G. Manuzio, G. Testera (University of Genoa), A. De Angelis, F. Scuri, F. Waldner (University of Udine), B. E. Bonner (Rice University), D. A. Church, S. Cornford, R. A. Kenefick (Texas A & M University), and J. Eades (CERN). This work was supported in part by the U. S. Department of Energy.

References

- [1] C. Stubbs, Proceedings of the 24th International High Energy Physics Conference, Munich, August 1988, to be published.

- [2] F. D. Stacey, G. J. Tuck, G. I. Mocre, S. C. Holding, B. D. Goodwin and R. Zhou, Rev. Mod. Phys. 59 (1987) 157; D. H. Eckhardt, C. Jekell, A. R. Lazarewicz, A. J. Romalides and R. W. Sands, Phys. Rev. Lett. 60 (1988) 2567; C. L. V. Aiken, M. E. Ander, M. Zumbargo et al., Proceedings of the 5th Marcel Grossmann Conference, Perth, Australia, August 1988, to be published.

- [3] T. Goldman, R. J. Hughes and M. M. Nieto, Phys. Lett. 171B (1986) 217 and Scientific American 258, no. 3 (1988) 48.

- [4] N. Beverini et al., CERN Proposal PSCC/86-2/P94; M. V. Hynes, Physica Scripta T22 (1988) 195.

- [5] L. M. Simons, Physica Scripta T22 (1988) 90.

- [6] M. H. Holzschelter, R. E. Brown, N. Jarmie and D. G. Lizon, Physica Scripta T22 (1988) 290.

- [7] N. Beverini, V. Lagomarsino, G. Manuzio, F. Scuri, G.

Testera and G. Torelli, *Phy. Rev. A* 38 (1988) 107.

[8] N. Beverini, V. Lagomarsino, G. Manuzio, F. Scuri, G.

Testera and G. Torelli, *Physica Scripta* T22 (1988) 238.

[9] J. M. Lockhart, F. C. Witteborn and W. M. Fairbank,

Phys. Rev. Lett. 38 (1977) 1220.

Figure Captions

Fig. 1. Schematic diagram of the proposed experiment.

Fig. 2. Time-of-release spectrum of particles stored in a multi-ring Penning trap. The horizontal scale corresponds to a range of 0.6 s and an energy scale of about 12 to 0 keV. The large peak on the left corresponds to externally-injected trapped protons.

Fig. 1