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.

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--87-2386

DE87 013159

TITLE ANTIPROTONS ARE ANOTHER MATTER

AUTHOR(S) Michael V. Hynes, P-15

SUBMITTED TO Proceedings of the Workshop and Symposium on the
Physics of Stored and Trapped Particles, Stockholm,
Sweden, June 14-18, 1987

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.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Antiprotons are Another Matter

Michael V. Hynes
Physics Division
Los Alamos National Laboratory
Los Alamos, NM USA 87545

Abstract

Theories of gravity abound whereas experiments in gravity are few in number. An important experiment in gravity that has not been performed is the measurement of the gravitational acceleration of antimatter. Although there have been attempts to infer these properties from those of normal matter, none of these theoretical arguments are compelling. Modern theories of gravity that attempt to unify gravity with the other forces of nature predict that in principle antimatter can fall differently than normal matter in the Earth's field. Some of these supergravity theories predict that antimatter will fall faster and that normal matter will fall with a small Baryon-number dependence in the Earth's field. All of these predictions violate the Weak Equivalence Principle, a cornerstone of General Relativity, but are consistent with CPT conservation. In our approved experiment at LEAR (PS-200) we will test the Weak Equivalence Principle for antimatter by measuring the gravitational acceleration of the antiproton. Through a series of deceleration stages, antiprotons from LEAR will be lowered in energy to ~ 4 Kelvin at which energy the gravitational effect will be measureable. The measurement will employ the time-of-flight technique wherein the antiprotons are released vertically in a drift tube. The spectrum of time-of-flight measurements can be used to extract the gravitational acceleration experienced by the particles. The system will be calibrated using H^- ions which simulates the electromagnetic behavior of the antiproton yet is a baryon to $\sim 0.1\%$. To extract the gravitational acceleration of the antiproton relative to the H^- ion with a statistical precision of $\pm 1\%$ will require the release of $\sim 10^6 - 10^7$ particles.

1 Introduction

How objects fall to Earth has been a topic of speculation and research in the written literature since the time of Aristotle [1] (in the Western cultural tradition). At issue in Aristotle's work and that of latter writers is the rate at which "heavy" objects fall to Earth compared to "light" objects. The resolution of this issue is by no means intuitively obvious. As young school children many of us can recall being puzzled by this issue and indeed many advanced young students do not appreciate that heavy and light objects fall at the same rate in the Earth's field. Aristotle reports exactly the opposite: Heavy objects fall faster than lighter ones. Although there is disagreement in some circles [2] that Aristotle is in fact referring to objects falling to the Earth, it is known that the pre-renaissance view widely attributed to Aristotle was that heavier objects fell faster. In this debate it could be that Aristotle is being blamed mistakenly for millennia of misunderstanding. More recently, G. Galilei has reported results that are contrary to this "Aristotelian" view [3]. In this work Galileo reports dropping heavy and light objects from a high tower in Pisa. All objects regardless of their weight or composition fell at the same rate. Galileo reports his results in the form of a dialog between Salviati (Galileo's pen name) and Simplicio (a theorist of that era). There is no doubt in Galileo's mind who was responsible for the common bias of the day; Aristotle was. However, Galileo's work which included rolling balls down inclined planes was not the only work of that era reporting on the behavior of objects falling to Earth. Indeed the early work of N. Tartaglia of Venice [4] and latter his student G. B. Benedetti [5] helped quantify the science of ballistics which was useful for blowing holes in more things than old theories attributed to Aristotle. Galileo however in about 1610 took all this work and added a new dimension, mathematics, and for the first time truly quantified the observations. Even his dialog with Simplicio testifies to this modern approach by giving not only the observation but also the error analysis. Lastly Galileo was the first to introduce the concept and terminology of "gravity" into the literature.

The same year that Galileo died, Newton was born. Newton built upon the observational work of T. Brahe and its analysis by J. Kepler to arrive at the first modern theory of gravity; the inverse-square law [6]:

$$m_I a = m_g \frac{GM_o}{r^2} \quad (1)$$

where G is the gravitational constant and M_o is the mass of the Earth. In this work we have the first development of the concepts of inertial and gravitational mass as distinct properties of objects. By assuming their equality for all objects independent of composition, all the results of Galileo and others can be explained. Thus Newton was the first to formulate what has become known as the Weak Equivalence Principle:

$$m_I = m_g \quad (2)$$

With this quantitative prediction several researchers sought to test the new result for objects falling to Earth [7,8,9,10]. All these workers reported, just as Galileo did, that

independent of an object's weight or composition, they all fell to Earth at the same rate. The most precise of this work in the modern era is that of R. V. Eötvös [9,10] and H. H. Potter [8] who report a precision of 1 part in 10^8 . For objects falling to the Sun the work of References [11] and [12] report precisions of 1 part in 10^{11} and 1 part in 10^{12} respectively for all objects falling at the same rate.

To A. Einstein in about 1916 the idea of the equivalence of the inertial and gravitational mass of an object seemed a "pretty sure thing". As a result the Weak Equivalence Principle became embodied in the theory of General Relativity (GR) as an axiomatic cornerstone; that is it is assumed at the outset without proof. Naturally one cannot now use GR to now prove the validity of the Equivalence Principle. However by this time the wording of the Equivalence Principle has gotten a bit more modern and that included in GR a bit more sophisticated. The various forms of the Equivalence Principle can be stated as

Given an arbitrary gravitational field there exists at every point in space time a "locally inertial coordinate system" such that

- ...the laws of motion of freely falling bodies (Weak Equivalence)...
- ...the laws of nature except gravity (Strong Equivalence)...
- ...the laws of nature including gravity (Einstein Equivalence)...

are form equivalent to those in an unaccelerated system in the absence of gravity.

Although the number and sophistication of the principles have increased the simplest equivalence, that of the universality of free fall as demonstrated by Galileo and many others, is embodied in all stronger versions.

While all this work was going on in gravity there was a great deal of activity in other areas of physics. Other forces in Nature were discovered: electromagnetic, nuclear, and weak. Special Relativity and Quantum Mechanics were developed. The concept and reality of elementary particles were established. The concept of antiparticles arose from the work of Dirac [13] in the early 1930's who for the first time joined special relativity and quantum mechanics. Thus the concept of antimatter in Nature arose some two decades after the advent of General Relativity. Quantum field theory became the preferred approach to describe the interaction of particles in terms of the exchange of yet other particles that mediate the force involved. Finally all the work in antiparticles and quantum field theory was unified into a symmetry principle, CPT symmetry, by Luders in 1954 [14], only a year before the discovery of the antiproton [15]. This symmetry principle states that an antiparticle is the CPT conjugate of the corresponding particle. This symmetry also states that all the *intrinsic* properties of antiparticles can be derived their CPT conjugates. This means that properties such as charge, magnetic moment, and inertial mass are all related; particle to antiparticle. However, CPT does not address properties such as gravitational mass which appears more as a coupling constant rather than as an intrinsic property. Thus

it is not CPT that leads to the common bias that the gravitational masses of particle and antiparticle are identical. This bias arises from the Equivalence Principle.

More recently, there have been attempts to unify gravity with the other forces of nature [16]. These attempts at unification are motivated by understanding of the early universe, the quantum mechanics of black holes, and other cosmological issues. However, gravity is extremely difficult to quantize. This difficulty arises from a fundamental incompatibility of concepts first observed by Wigner in 1957 [17]. In General Relativity all particles follow well defined trajectories, world lines, through four dimensional space-time. In quantum mechanics the existence of a well defined trajectory is an anathema due to the Heisenberg Uncertainty Principle. Nevertheless gravity has been quantized under restrictive assumptions. However the unification with other forces requires the introduction of additional components to the conventional graviton exchange. Because these additional components couple to Baryon number or Lepton number they manifestly violate the Weak Equivalence Principle.

Our experiment at LEAR (PS-200) to measure the gravitational acceleration of the antiproton [18] will for the first time test the Equivalence Principle for antimatter. This experiment is a collaboration between the University of Pisa, Los Alamos National Laboratory, Rice University, Texas A & M University, University of Genoa, CERN, and NASA/Ames Research Center. The measurement of this acceleration was first proposed at CERN by the Pisa-Genoa group [19], and has been discussed as an experiment at LEAR since the early planning stages for this facility [20]. Our experiment has no earlier precedent [21]. Although several attempts have been made to anticipate the result [22,23,24], none are compelling as to the numerical value in the light of the new work on supergravity theories.

2 Supergravity Theories

The modern field theories that have grown from General Relativity involve the exchange of the graviton which is a spin=2 particle. Consequently, the resulting force can only be attractive, regardless of whether or not the interaction is between matter-matter or matter-antimatter. Even the Brans-Dicke theories which involve in addition the exchange of a scalar partner to the graviton, have only attractive forces. However, the gravity theories that have grown from attempts to unify all the forces of nature including gravity, supergravity theories, have tensor ($spin = 2$), vector ($spin = 1$), and scalar ($spin = 0$) exchanges. The important addition in these theories for the antiproton gravity experiment (PS-200) is the vector term, because this term will change sign depending on whether the interaction is between matter-matter or matter-antimatter. Independent of these theories the experiment will measure a model independent quantity, the magnitude of the isospin antisymmetric component of gravity on the Earth's surface. Because the supergravity theories give a specific framework in which to examine experimental sensitivities, we consider them here in some detail.

2.1 Supergravity Phenomenology

In supergravity theories the potential is of the form

$$V(r) = -\frac{Gm_1}{\gamma r} [(2\gamma^2 - 1) \mp a\gamma e^{-r/v} + b e^{-r/s}] \quad (3)$$

where m_1 is the mass of the point source particle considered to be at rest, r is the distance from this particle, G is the gravitational constant, a (b) is the strength of the vector (scalar) component, v (s) is its range, and γ is the relativistic factor referring to the test particle. For the vector component the upper sign is for matter-matter interactions and the lower sign is for matter-antimatter interactions.

For experiments measuring gravitational effects at or above the Earth's surface, the above potential has to be integrated over all source points (i.e. over the volume of the Earth) to derive the total gravitational potential of the Earth. In addition, to derive the total gravitational force acting on a test particle, the gradient of this potential has to be taken to arrive at

$$F(r) = -\frac{4\pi\rho Gm}{\gamma r^2} \left[\frac{R^3}{3} (2\gamma^2 - 1) \mp a\gamma v R(v+r) e^{-r/v} \cosh\left(\frac{R}{v}\right) \pm a\gamma v^2(v+r) e^{-r/v} \sinh\left(\frac{R}{v}\right) \right. \\ \left. + bsR(s+r) e^{-r/s} \cosh\left(\frac{R}{s}\right) - bs^2(s+r) e^{-r/s} \sinh\left(\frac{R}{s}\right) \right] \quad (4)$$

where R is the Earth's radius, ρ is the Earth's density, $r = R + h$ with h the altitude above the Earth's surface, and m is the mass of the test particle. In this derivation it is assumed for simplicity that the Earth is spherical and of uniform density.

2.2 Experimental Sensitivities

In our experiment to measure the gravitational acceleration of the antiproton, the technique proposed (see the next section) will measure exactly that, the gravitational acceleration, or force per unit mass of the antiproton relative to that of the proton which will be used as a calibration standard. Thus the best known quantity in this experiment is the difference between the gravitational acceleration of the antiproton and proton. In addition this experiment will be executed at the Earth's surface. Equation 4 can be used to solve for what parameters, in the context of supergravity theories, this difference of accelerations is sensitive to. Using the sign convention that positive acceleration is toward the Earth's center, we have that

$$\Delta g = g_p - g_{\bar{p}} = \frac{8\pi\rho G}{r^2} \left[avR(v+r) e^{-r/v} \cosh\left(\frac{R}{v}\right) - av^2(v+r) e^{-r/v} \sinh\left(\frac{R}{v}\right) \right] \quad (5)$$

where $r = R$ at the Earth's surface and we have taken $\gamma = 1$. Evidently from this expression the difference of accelerations is sensitive only to the range and strength parameters of the vector component of the supergravity potential (Eq. 3).

Figure 1: Contours of constant $\Delta g/g_0$ for the antiproton-proton gravity experiment, plotted on a grid of a versus v (see text also).

To get a feel for the magnitudes involved in Eq. 5, let us normalize Δg by the acceleration of gravity expected from conventional theories

$$g_0 = \frac{4\pi\rho G R^3}{r^2} \frac{1}{3} \quad (6)$$

Thus we have that

$$\frac{\Delta g}{g_0} = \frac{6av}{R^3} \left[R(v + \tau) e^{-\tau/v} \cosh\left(\frac{R}{v}\right) + v(v + \tau) e^{-\tau/v} \sinh\left(\frac{R}{v}\right) \right] \quad (7)$$

This equation can be simplified by assuming that $h/R, v/R \ll 1$. Keeping terms up to second order in h/R or v/R we have that

$$\frac{\Delta g}{g_0} = \frac{3av}{R} e^{-h/v} \left[1 + \frac{h}{R} \right] \quad (8)$$

where once again h is the elevation above the Earth's surface. Equation 8 shows that the product of av is determined.

Because the above expression is a function of only two theoretical parameters, we can plot contours of constant $\Delta g/g_0$ on a grid of range and strength of the vector component. Such a plot is displayed in Figure 1 where $r = R$ (at the Earth's surface). Each of the contours shown corresponds to the value of $\Delta g/g_0$ indicated. Because the quantity

Δg is experimentally determined in the antiproton gravity experiment, these contours can be used to determine the range of a and v values that would be consistent with a given measurement. For example, let us assume that the experiment measures a 10% difference between the gravitational acceleration of the antiproton and the proton. The 0.10 contour in Fig. 1 maps out the set of a and v values that are determined by this measurement. Naturally, the measured deviation will have an experimental error bar associated with it. Such an error bar will correspond in the Figure to a band of acceptable values centered around the 0.10 contour. Alternatively, the experiment may detect no deviation in acceleration but only be sensitive at the 10% level. Thus a 10% upper limit will be set by such a measurement. The range of acceptable a and v values determined by this hypothetical upper limit would lie below the 0.10 contour. All values of a and v lying above this contour would be ruled out.

Experimentally, the antiproton gravity experiment is being designed to measure gravitational acceleration near that of conventional gravity theories to about 1%. Thus it should be possible in this experiment to set a 1% upper limit or to measure a 10% difference between the accelerations of antiprotons and protons with a 10% error band. In either case only ranges of acceptable a and v values are determined or ruled out. If a difference between the gravitational accelerations of antiprotons and protons is in fact measured, there will be a tremendous motivation to determine a and v separately. The only other experimental "knob" at our disposal in the antiproton gravity experiment is the altitude at which it is executed. By letting $r = R + h$ in Eq. 8 where h is the altitude above the Earth's surface, the contours of constant $\Delta g/g_0$ will change. If by some miracle such an altitude change is experimentally possible, then in principle this measurement can determine a and v separately. Naturally, a finite error band for each contour will determine a and v to within a small patch in the $a - v$ plane corresponding to the overlap of the two error bands.

Although the antiproton gravity experiment is being designed to execute a measurement of the gravitational acceleration of the antiproton relative to the proton, it is possible that the systematic errors will be under sufficient control to allow for an absolute measurement. If an absolute measurement is possible, then a new opportunity in the analysis is available. By forming the average of the antiproton and proton accelerations in the context of supergravity theories it can be shown that the product of the range and strength of the scalar component bs can be determined. Just as for the vector component, a measurement at the surface and at an elevation can be combined to determine b and s separately.

All of these additional measurements at elevations and that done absolutely are hypothetical in nature and are extremely difficult experimentally. What our experiment can measure is the difference of the accelerations of antiprotons relative to protons. As we have seen, this measurement is not sufficient to determine all the parameters of the phenomenological formulations of the supergravity theories. Thus additional experiments are required. At present many experiments are in progress to measure deviations from conventional gravity using normal matter falling in the Earth's field. This work together

with our antiproton measurement can be analyzed in the context of supergravity theories and will allow a more complete determination of the parameters. However, even if the normal matter experiments measure a null result, the acceleration for the antiproton could in principle be different from that of the proton. The two sets of measurements are thus complementary and indeed required for a full understanding of these theories.

3 The Gravity Measurement

The gravitational force is the weakest of the forces in nature. To measure the effect of gravity on antiprotons, all sources of non-gravitational force must be controlled at a level sufficient for the gravitational effect to be dominant. To provide an orientation to the magnitudes of quantities involved in the measurement, we introduce the three main areas which are potential sources of the uncertainties in our experiment:

1. Of overriding importance is the size of the expected gravitational effect relative to other experimental parameters. Because antiprotons are charged and have a magnetic moment, we can expect that the electromagnetic forces could be a source of difficulty in our time-of-flight (TOF) measurement.
2. Not all launched particles will have a TOF signature applicable to extracting information on the gravitational acceleration. The correlation between the experimental design and the statistics necessary for a given precision needs to be carefully examined.
3. An absolute TOF measurement is clearly more difficult than a relative one. A calibration reference of known gravitational mass with electromagnetic properties nearly identical to those of the antiproton is needed. The H^- ion will satisfy this requirement.

3.1 The Measurement Scale

The scale of the electric field that must to be controlled can be estimated by equating the electric and gravitational forces on an antiproton;

$$E = \frac{m_p g}{e} = 1.03 \times 10^{-7} \frac{V}{m}. \quad (9)$$

Stray electric fields in the experiment need to be substantially less than this to observe the gravitational force on antiprotons. The pioneering work of Witteborn and Fairbank [25] on the gravitational properties of electrons reported that stray electric fields could be controlled at the level of 10^{-11} V/m.

The scale of magnetic field gradients that need to be controlled can be determined similarly by noting that the force on a magnetic moment, μ , from a magnetic field will be given by

$$\mathbf{F} = (\mu \cdot \nabla)\mathbf{B}. \quad (10)$$

If the magnetic field is uniform in all but the z-direction, then

$$F = \mu_z \frac{dB}{dz}, \quad (11)$$

which acts along z. For an antiproton in a magnetic field, the effective magnetic moment will be a combination of the intrinsic moment (the nuclear magneton) and the orbital moment which is dominant. By setting the magnetic gradient force equal to the gravitational force we have that

$$\frac{\Delta B}{B} \frac{1}{\Delta z} = \frac{g\hbar e}{2\mu_N c k T} = 1.19 \times 10^{-3} \frac{1}{T} (m^{-1}). \quad (12)$$

where T is in K and Δz is in meters. The ratios $\Delta B/(B\Delta z)$ we need to be concerned with then are substantially smaller than 10^{-3} to $10^{-4} m^{-1}$ for 1 - 10 K antiprotons. Still more stringent requirements will be placed on the magnetic field gradient, for higher temperature antiprotons.

To set the energy scale for the measurement, we note that the gravitational potential energy difference for a distance L is given by $U = mgL$. For L = 1 m the energy involved is

$$\begin{aligned} U &= 1.6 \times 10^{-26} J \\ &= 1.03 \times 10^{-7} eV \\ &= 1.19 \times 10^{-3} K. \end{aligned}$$

This amount of energy is very small, but not unmeasurable. In fact it is three orders of magnitude larger than for electrons, on which previous measurements were reported [26].

3.2 The Time-of-Flight Technique

The time-of-flight technique for the measurement of the gravitational acceleration of matter can be traced back to Aristotle [1] who reported that heavier bodies fall faster than light ones. Some systematic error in observation no doubt. More recently G. Galilei reported [3] the currently accepted results on the same experiment. In the modern era the time-of-flight technique has been used by Witteborn and Fairbank [25,26] to measure the gravitational properties of electrons. In their approach, electrons with very low velocities were launched vertically up a conducting drift tube. The arrival at the top of the drift tube was detected by a electron multiplier and the time-of-flight was recorded. Because the initial velocity of the electrons was thermally distributed, what they measured through many repetitions

Figure 2: A one-dimensional Maxwell-Boltzmann distribution of velocities for temperatures as indicated (see text also).

was the distribution function for the time-of-flight given a distribution of initial velocities. In the analysis of their data many systematic [25] effects were included.

Let us first consider what the time-of-flight (TOF) spectrum for particles launched vertically would be when acted upon only by gravity. In general, for a particle with initial velocity v_o , the time-of-flight either up (upper signs) or down (lower signs) a drift space of length L will be

$$t = \int_0^L \frac{dz}{\sqrt{v_o^2 \mp 2gz}} = \frac{v_o}{g} \left(\pm 1 \mp \sqrt{1 \mp \frac{2gL}{v_o^2}} \right). \quad (13)$$

We know from energy considerations alone that the energies and hence the velocities, involved here for meter-like values of L are very low. The value of v_o will not be a fixed value but will be distributed according to a thermal distribution. Assuming a Maxwell-Boltzmann (MB) distribution, the one dimensional distribution for v_o can be written as

$$dN(v_o) = \sqrt{\frac{m}{2\pi kT}} \exp\left(-\frac{mv_o^2}{2kT}\right) dv, \quad (14)$$

where the velocities range from $-\infty < v < +\infty$ and the distribution over this range is normalized to 1.0. This distribution for v_o is plotted in Figure 2 for several temperatures between 2 and 10 K. The width of these distributions increases with increasing temperature whereas the likelihood for low velocities decreases. The number of particles at low velocities is an important parameter in the TOF spectrum because of their relative sensitivity to

gravitational effects. Therefore the initial temperature of the particle distribution should be as low as possible.

The TOF spectrum resulting from a Maxwell-Boltzmann distribution of velocities can be derived by using Eq. 13 to relate t to v and dt to dv . Let us consider the TOF distribution for upward launching. The characteristics of this distribution can be seen physically by considering the situation; we toss a particle upward with some initial velocity. We measure how long the particle takes to rise to an elevation L . For very large initial velocities this time is very short. The effect of gravity on the TOF for these particles is vanishingly small. However, in the TOF distribution there is a long tail toward late times, arising from the low velocity component of the MB distribution. As the initial upward velocity of the particles decreases, the time-of-arrival at L increases until eventually the initial velocity is just enough for the particle to reach L before it turns around and falls back down. This cutoff velocity is given by

$$v_c = \sqrt{2Lg}. \quad (15)$$

Using Eq. 13, the time required to reach L is given by

$$t_c = \sqrt{\frac{2L}{g}}. \quad (16)$$

There are no more arrivals after t_c because the initial velocity was insufficient to reach L . The TOF distribution function near the cutoff time is shown in Figure 3 for $L = 1m$ and several temperatures. From the figure we see that the lower the temperature, the more steeply the distribution function approaches the cutoff. For higher temperatures there are fewer and fewer low velocity particles (see Figures 2 and 3) and the distribution flattens at the cutoff. The cutoff time is determined by conservation of energy and thus is independent of the details of the distribution function.

In our TOF approach with a distribution of initial velocities, one is looking at endpoints of TOF distributions where the sensitivity to the gravitational effect is maximal. By extracting from the data the value of the TOF endpoint Eq. 16 can be used to extract the gravitational acceleration of the particles involved (given ideal measuring conditions).

Naturally to determine the endpoint the TOF for many particles will have to be measured to assemble enough counts in the spectrum near the endpoint. The measurement is thus a statistical one. To estimate the number of particles needed for the experiment we have simulated the late-time part of the TOF spectrum near the endpoint and fit the generated spectra using a fitting function based on the TOF distribution function. By varying the number of events in the spectrum we can study how sensitive the precision in the measurement of g is to the total particle number in the measurement. In this analysis we have also added a 1 mm error in our knowledge of L . The results of this study are displayed in Figure 4 in which the relative error σ_g/g is plotted versus the total number of particles in the measurement. The results for 1 and 10 K temperatures are shown for a drift length of 100 cm. The experimental design will provide between 10^6 to 10^7 antipro-

Figure 3: Late-time TOF distribution for upward launch using a MB distribution of initial velocities for temperatures as indicated. Note cutoff (see text also).

Figure 4: Relative error in gravitational acceleration versus total number of particles in the measurement.

tons. This will allow about a 1 % measurement of g . This discussion has left out all the systematic errors that will affect the data and degrade the accuracy of the measurement.

3.3 Calibration with H^- Ions

Absolute measurements of gravitational effects, although important, are not the central focus of our experiment. Rather, we propose to test the universality of free fall for antiprotons relative to protons. Supergravity theories predict that antiprotons will fall faster in the Earth's gravitational field than will protons. This is in essence a relative statement. We propose then, to calibrate our equipment using H^- ions and to perform a relative experiment using antiprotons and H^- ions. An input parameter in the calibration process will be the local gravitational acceleration at CERN [28].

$$g = 980.711 \text{ cm/sec}^2 \quad . \quad (17)$$

With this knowledge in advance, the TOF spectrum of particles can be measured and used to determine all non-gravitational effects in the apparatus. Naturally, these effects need to be controlled in the experimental design as much as possible. However, their net effect on antiprotons can be determined using "other particles". This statement is true provided that interaction of the antiprotons with the non-gravitational effects is the same as for the other particles. To preserve the comparison of baryon and antibaryon, these other particles should be baryons so that the gravitational effects are calibrated for baryon-like interactions. For non-gravitational effects these other particles should mimic antiprotons as closely as possible. Because these non-gravitational effects are electromagnetic in character, the "other particles" should have the same charge and magnetic moment as the antiproton. Fortunately, the H^- ion has the same charge and nearly the same magnetic moment as the antiproton. The reason for the same charge is obvious, the reason for the magnetic moment similarity is a bit subtle. The two electrons in the H^- ion are coupled to spin zero, but because of the Coulomb repulsion between them, they are anticorrelated in their orbits. This anticorrelation leads to diamagnetism for the H^- ions (and for Helium also) [27]. Thus, the magnetic moment arising from the electrons in the H^- ion is an induced effect which increases linearly with magnetic field strength. The total effective magnetic moment of the H^- ion in a magnetic field is a combination of the orbital moment, the intrinsic nuclear moment, and the induced electron moment. For the complete range of temperature and magnetic field strength in which the experiment will operate, the orbital moment dominates.

The H^- ion will mimic the behavior of the antiproton in electric and magnetic fields allowing us to calibrate these effects. Additionally, D^- or other negative ions with different masses can be used in the calibration process as a further check on the electromagnetic effects present in the drift space.

In addition to being a calibration standard for the drift space, H^- ions can also be used to test the low energy beam line and ion trap system. Thus we can tune these systems for

maximal transmission before antiprotons are used. We propose therefore, to incorporate in our experimental set-up, an H^- ion source with the appropriate energy and energy spread to test the beam line and ion trap systems. For some of these tests protons will be used because they are more robust with respect to collisions.

Finally, we need to consider the detection of the H^- ions versus antiprotons. Naturally, it is important to detect these particles in the same device so that the stray field effects on the drift time are the same. Because of their very low velocity, the H^- ions will not be detectable in devices like scintillators although antiprotons could be readily detected in them. For most devices the energies of the particles we wish to detect are too low for any secondary emission processes. To use any detector based on secondary emission will require an extraction stage at the exit of the drift tube to accelerate the particles before they enter the detector. We are considering a variety of electron multipliers, including microchannel plates. In addition a detector not based on secondary emission is being pursued by the Pisa group [29,30]. This detector is a calorimeter of extreme sensitivity. The selection of the final detector will be made on the basis of the efficiency in the low temperature and magnetic field environment of the drift tube.

3.4 Experimental Design

To measure the gravitational effect on antiprotons, the antiproton energy has to be sufficiently low for the TOF spectrum to have sufficient particles near the cutoff time $t_c = \sqrt{2L/g}$ so that a fit to the TOF spectrum will extract t_c with precision. The lowest energy beam currently available from LEAR is ~ 2 MeV (Ref. [31]). To perform the measurement, this energy has to be reduced by about thirteen orders of magnitude. We propose a series of deceleration stages involving an RFQ decelerator, or possibly a degrading foil, and several pulsed electromagnetic ion traps to accomplish this energy reduction. The final ion trap will store up to 10^7 antiprotons in a distribution at ~ 10 K or lower. Once the particles are cold enough, they will be released into a vertical drift tube. After a 1 m flight path, the arrival times of the antiprotons relative to the launch time will be measured.

3.5 Experimental Overview

The experiment subdivides into four different components determined by the particle energy and on the techniques involved in manipulation and storage:

- The deceleration beam line
- The catching trap
- The transfer beam line
- The ultra-low energy beam line

Figure 5: Schematic view of the experimental setup indicating major equipment items (see text also).

A schematic view of the experimental setup is shown in Fig. 3.1.

The deceleration beam line will lower the 2 MeV extracted LEAR beam to a few tens of keV, an energy suitable for trapping particles. At present, two options to accomplish this are being considered: a radio frequency quadrupole (RFQ) decelerator and a degrading foil. The RFQ has been designed and its performance characteristics quantified. Due to the large emittance of the fast extracted LEAR beam, the transmission efficiency of the RFQ in lowering the 2 MeV beam to 20 keV is expected to be about 7%. This can be improved to 50 - 70 % if electron cooling is used in the LEAR ring. However, recent calculations for a foil degrader indicate transmission/capture efficiencies near 12% for particles below 50 keV are possible. The difficulty with this option is the lack of data for antiproton energy losses from an initial energy of a few MeV down to a final energy of a few tens of keV. Before a technical decision can be made the calculations will be checked with a measurement.

The vacuum requirements for the experiment are set by the survival times of the particles, the annihilation rate of the antiprotons and the charge exchange rate for the H^+ ions with the residual gas. The annihilation rate at low velocities depends only on the density of residual gas atoms and for the 4 K environment of the final launching trap one finds that a vacuum of 10^{-14} to 10^{-15} Torr is necessary for containment times of a few hours. To attain these pressures we will use a closed cryogenic 4 K system in which 10^{-14} Torr and lower is achievable [32]. H^+ survival at this pressure is not a problem.

The catching trap is not required to run at a low temperature, and the vacuum requirement for the antiproton is less severe. For a room temperature trap, 10^{-12} Torr is needed to give an antiproton the lifetime of several hours which will be necessary for the cooling times expected. Such a pressure is possible with care. In addition, the H^- ion life may be short enough to require an alternative way of filling the final trap with cooled particles. Several alternatives, including production internal to the trap or direct insertion from an ion source with a narrow energy spread, are under study.

The catching trap, the first stage of the trapping system, is designed to accept a beam burst from the deceleration beam line at several tens of keV and to store it for periods of up to several hours while cooling the particle energies to between 1-10 eV. Finally, this trap is designed to eject the cooled bunch with an emittance matched to the downstream acceptances. The detailed design of this trap depends on the deceleration option that is selected. The principle design parameter that is optimized is the total number of trapped antiprotons. The trapping sequence starts with entrance electrodes at ground as the beam-burst enters the trap. The downstream electrode is at several 10's of kV. As the particles transit the trap they will decelerate against this downstream potential, turn and go back. Before the particles can exit the trap on the return pass, the potential on the entrance electrode is quickly raised to several 10's of kV. The particles thus cannot exit; they are caught. In the multiring Penning trap we have designed for the catching trap, the particles are confined in a harmonic electrostatic well in the direction of their initial momentum and confined radially by a large (6 T) magnetic field. While oscillating in this trap, the induced image currents in the trap electrodes can be used to extract energy from the confined particles either passively (resistive cooling) or actively (Stochastic cooling). In addition, a cloud of cold electrons can be introduced in the trap to collisionally cool the trapped antiprotons. The selection of cooling technique is a matter of rate. At present, only resistive cooling is a well established technique, but with slower than optimal cooling rates in our multiring trap design. We are studying the other approaches which could be significantly faster. In any event, as discussed earlier, annihilation rates due to collisions with residual gas atoms have $t_{1/2} \sim 4.8$ hrs for 1 eV antiprotons at 10^{-12} Torr. Thus resistive cooling is in principle fast enough. Once the particles are cooled to 1-10 eV, they will be ejected from the trap at ~ 1 keV. To match the acceptance of the downstream trap, and allow for some emittance growth in the transfer beam line, the transverse cloud size in the catching trap will be reduced using the sideband centering technique [33]. In addition, the magnetic field will be reduced to allow an easier match to the transfer beam line optics. After deceleration, catching, and cooling to 1 eV we expect to have between 10^6 - 10^7 antiprotons being transferred to the ultra low energy beam line.

The transfer beam line is designed to transport the cooled antiprotons from the catching trap which is mounted in a horizontal configuration, to the cooling trap at the base of the ultra low energy beam line which is mounted in a vertical configuration. The design concept for this beam line is driven by the pinning of the particle orbits to the field lines of the catching trap solenoid. The concept at present is to connect these field lines to the

field-lines of the vertical solenoid using an array of pulsed magnets. Ray trace calculations indicate that the particles can be transported with high efficiency to the cooling trap with minimum emittance growth. However, because of the energy spread in the burst and the ~ 2 m flight path, a debunching/deceleration stage must precede the entrance to the cooling trap.

The ultra-low energy beam line is the heart of the gravity measurement. It has 3 major elements; the cooling trap, the drift tube, and the detector. Because of the ultra-high vacuum requirements ($\leq 10^{-14}$ Torr) this entire system is cryogenic, operating at liquid helium temperatures (~ 4.3 K).

The cooling trap is designed to reduce the particle energy to ~ 4 K (0.8 meV), and to release the particles, a few at a time either directly into the drift tube or into an intermediate trap. The issue of release is under design study. The central design issue is to obtain particles in the drift region at the 10^{-7} eV level. This energy is comparable with the gravitational potential difference for an antiproton over 1 m.

The drift tube is designed to shield the drifting particles from external electric fields. However, surface effects on the inside of the tube can generate large non-uniform internal electric fields unless special precautions are taken. In particular, we will study amorphous conducting coatings as well as making the entire drift tube out of a single crystal. Both these approaches could suppress the surface fields to an acceptable level.

The detector, at the exit of the drift tube, must be capable of detecting both antiprotons and H^- ions in the same experimental configuration. Although the antiprotons could be detected easily, due to the annihilation products, the very low energy H^- must be accelerated to be detected in secondary emission devices. Several detector options have been identified and are under study.

An external ion source will also be used to exercise the catching trap and all downstream beam line elements. We plan at present to locate the source upstream of the catching trap and to use it to provide very intense bursts of H^- or protons at several kilovolts.

4 Summary

The experiment to measure the gravitational acceleration of the antiproton at LEAR (PS-200) has no precedent. This measurement will test the Equivalence Principle for antimatter falling in the Earth's gravitational field. Modern theories of gravity predict that the antiproton could fall faster than protons. However, to determine all the parameters of these new theories will require both the results from our experiment as well as those of normal matter experiments. Nevertheless our experiment will measure a model independent quantity, the isospin antisymmetric component of the Earth's gravitation field.

Our experimental approach is based on the time of flight technique used in earlier work on the electron, but has some important advantages. In particular there is a calibration standard, the H^- ion, which simulates the electromagnetic behavior of the antiproton

yet is a baryon to high precision. Thus we will perform a relative measurement of the acceleration of antiprotons as compared to H^- ions. To measure this relative quantity to $\sim 1\%$ will require the release of $\sim 10^6$ antiprotons. Many repetitions of this release will be used to determine systematic effects and an error band.

References

- [1] Aristotle, *De Caelo*, 2.13.294b 3-6; *Physics* 4.8.215a 25-31; see "The Works of Aristotle", by J. L. Stocks, W. D. Ross, ed., Oxford University Press (1922).
- [2] L. Cooper, "Aristotle, Galileo, and the Tower of Pisa", Cornell University Press (N.Y.), 1935.
- [3] G. Galilei, *De Motu* (1590) (see *Le Opere Di Galileo Galilei*, Edizione Nazionale, 1. 262-3); *Discorsi e Dimonstrazioni Matematiche Intorno a Due Nuove Scienze Attenenti alla Mecanica e i Movimenti Locali...* Leyden (1638); (see *Ed. Naz.* 8.108-9).
- [4] N. Tartaglia (1499-1557), "Quesiti et Inventioni diversi", Venice, 1546.
- [5] G. B. Benedetti (1530-90), "Demonstratio Proportionum Motuum localium contra Aristotelem et omnes Philosophos", Venice, 1554.
- [6] I. Newton, *Principia*, London (1686).
- [7] F. W. Bessel, *Pogg. Ann.* 25, 401 (1832).
- [8] H. H. Potter, *Proc. Roy. Soc. (London)* 104, 588 (1923); 113, 731 (1927).
- [9] R. V. Eötvös, *Math. Nat. Ber. Ungarn* 8, 65 (1890).
- [10] R. V. Eötvös, D. Pekar, and E. Fekete, *Ann. Phys. (Leipzig)* 68, 11 (1922).
- [11] P. G. Roll, R. Krotkov, and R. H. Dicke, *Ann. Phys. (N. Y.)* 26, 442 (1967).
- [12] V. B. Braginski and V. I. Panov, *Sov. Phys. JETP* 34, 463 (1972).
- [13] P. A. M. Dirac, *Proc. Roy. Soc.* A126, 360 (1930); A133, 60 (1931).
- [14] J. Lunders, *Kgl. Dan. Vid. Sel. Mat. Fys. Medd.* 28, no. 5 (1954); J. S. Bell, *Proc. Roy. Soc. (London)* A231, 479 (1955).
- [15] O. Chamberlain, E. Segre, C. Wiegand, and T. Ypsilantis, *Phys. Rev.* 100, 1947 (1955).
- [16] J. Sherk, *La Recherche* 8, 878 (1977); *Phys. Letts.* 88B, 265 (1979).

- [17] E. Wigner, *Rev. Mod. Phys.* 29, 255 (1957).
- [18] N. Beverini, J. H. Billen, B. E. Bolner, L. Bracci, R. E. Brown, L. J. Campbell, D. A. Church, K. R. Crandall, D. J. Ernst, A. L. Ford, T. Goldman, D. B. Holtkamp, M. H. Holzscheiter, S. D. Howe, R. J. Hughes, M. V. Hynes, N. Jarmie, R. A. Kenefick, N. S. P. King, V. Lagomarsino, G. Manuzio, M. M. Nieto, A. Picklesimer, J. Reading, W. Saylor, E. R. Siciliano, J. E. Stovall, P. C. Tandy, R. M. Thaler, G. Torelli, T. P. Wangler, M. Weiss, F. C. Witteborn, PS200 proposal, Los Alamos National Laboratory report LAUR-86-260.
- [19] N. Beverini, L. Bracci, V. Lagomarsino, G. Manuzio, R. Parodi, and G. Torelli, CERN/PSCC 83-14, PSCC/P68-19/3/83.
- [20] G. Torelli, *Proceedings of the Karlsruhe Workshop*, Note 16 (1979); V. Lagomarsino, G. Manuzio, and G. Torelli, CERN/PSCC/79-60 CERN/PSCC-I11/6/12/79.
- [21] T. Goldman and M. M. Nieto, *Phys. Letts.* 112B, 437 (1982).
- [22] P. Morrison, *Am. J. Phys.* 26, 358 (1958).
- [23] M. L. Good, *Phys. Rev.* 121, 311 (1961).
- [24] L. I. Schiff, *Proc. Nat. Acad. Sci.* 45, 69 (1959); *Phys. Rev. Lett.* 1, 254 (1958).
- [25] F. C. Witteborn and W. M. Fairbank, *Rev. Sci. Inst.* 48, 1 (1977).
- [26] F. C. Witteborn and W. M. Fairbank, *Phys. Rev. Lett.* 19, 1049 (1967).
- [27] H. J. Bethe and E. E. Saltpeter, "Quantum Mechanics of One and Two Electron Atoms", Academic Press, New York (1957), p. 227.
- [28] Based on the international gravity formula, *Handbook of Geophysics*, MacMillan and Co., (N.Y.), 1961, pp. 12-68.
- [29] G. Gallinaro, *Il Nuovo Saggiatore* 2, 2, 49 (1986).
- [30] E. Fiorini and T. O. Niimikoski, *Nucl. Instrum. Methods* 224, 83 (1984).
- [31] D. Allen, E. Asseo, S. Baird, J. Bengtsson, M. Chanel, J. Chevallier, R. Giannini, P. Lefevre, F. Lenardon, R. Ley, D. Manglunki, E. Martensson, J. L. Mary, C. Mazeline, D. Mohl, G. Molineri, J. C. Perrier, T. Pettersson, P. Smith, G. Tranquille, and H. Vestergaard, "Performance Update on LEAR," CERN/PS 87-26 (LEA), March 1987; and references therein.
- [32] W. Thompson and S. Haurahan, *Jour. Vac. Sci. Tech.* 14, 643 (1977).
- [33] D. J. Wineland and H. G. Dehmelt, *Intl. Jour. Mass Spec. Ion Phys.* 16, 251 (1975).