An Antihydrogen Interferometer for Measuring Antimatter Gravity

Thomas J. Phillips
Duke University
Durham, NC 27708

Abstract

The gravitational force on antimatter has never been directly measured, largely because electromagnetic forces overwhelm gravitational forces and no form of low-energy neutral antimatter has been available. However, the technology to make low-energy antihydrogen is currently being developed. We have designed an atomic interferometer that can measure the force of gravity on hydrogen or antihydrogen using a phase shift caused by gravity. The initial stage of the project is a demonstration experiment that will measure the gravitational force on hydrogen. A precise difference measurement between hydrogen and antihydrogen would be capable of detecting a new force that couples differently to matter and antimatter. This paper describes the proposed experiment and current progress towards realizing the measurement.

1 Motivation

It is a common belief that gravity is well understood, yet experimental measurements of gravity on the largest scales strongly disagree with theoretical predictions. Vast quantities of dark matter and a cosmological constant are postulated to reconcile the theory with the data. An alternate explanation is that our understanding of gravity is wrong, as was the case in an earlier "missing mass" problem where the planet Vulcan was postulated to explain the anomalous perihelion shift in Mercury's orbit. Clearly it is important to test our understanding of gravity to see if the current discrepancies between data and theory also have a more fundamental source.

Most physicists believe that the gravitational interaction does not distinguish between matter and antimatter, but this belief is not based upon any direct experimental evidence. Rather, it is based upon our understanding of general relativity (GR), which is a classical theory incompatible with quantum mechanics and with quantum field theory. The disagreement between the energy of the vacuum predicted by quantum field theory and the upper limit allowed by general relativity is over 120 orders of magnitude, making it possibly the largest disagreement in physics. While a viable quantum theory of gravity has not been

devised, the best hope for developing such a theory, models based on supergravity, generally include violations of the inverse-square law and/or the equivalence principle, and some include repulsive gravity [1, 2]. It may even be possible to incorporate a repulsive gravitational force between matter and antimatter within the framework of GR [3]. Clearly, the assumption that gravity does not distinguish between matter and antimatter should be tested. A measurement differing from our expectations would be a major discovery and would lead to a much better understanding of gravity and our universe in general.

An experiment to measure the gravitational acceleration of antimatter would also be sensitive to new forces weaker than gravity that couple differently to matter and antimatter. A sufficiently accurate measurement can test for weak fifth forces beyond what is inferred from equivalence-principle measurements [4]. In addition, even if all the measurements turn out just as physicists expect, there will still be great public interest in the results. The public is fascinated with antimatter, and even among those who know that antimatter is not just science fiction, many do not know whether it should fall up or down. This is the kind of experiment that the general public can understand, and it is this kind of experiment that can generate positive public relations for the field.

2 Measuring $\overline{g}$

The gravitational acceleration of antimatter has never been directly measured. The Witteborn-Fairbank experiment [5] gave inconclusive results for electrons, and they did not measure positrons. Measuring the gravitational force on charged particles is problematic [6], so a measurement with neutral antimatter is preferable. Of the neutral antimatter candidates, antineutrons have been produced only at high velocity, and the annihilation cross section is too high at low velocity to slow them efficiently. Positronium is also neutral, but it is unstable and it is only half antimatter. Antihydrogen has also been produced at relativistic velocities, but because its constituents are charged, they can easily be manipulated and it should be possible to produce low-velocity antihydrogen.

A number of ideas have been presented for ways to measure the gravitational force on antihydrogen [7, 8, 9]. However, these methods require the ability to capture a substantial number of antihydrogen atoms in traps. Since producing antihydrogen and then capturing it in a neutral-particle trap is much more difficult than producing antihydrogen without catching it, a neutral antimatter gravity experiment that does not rely on trapping neutral atoms should be much easier to perform. This is the kind of experiment described below.

2.1 Making slow antihydrogen

The ingredients for making slow antihydrogen are cold antiprotons and a cold, dense gas of positrons. The technology exists for producing both of these ingredients. Antiprotons have been caught and cooled in Penning traps by two different groups at LEAR [10, 11]. Antiprotons are decelerated to a very low energy and directed into a Penning trap through a thin window that degrades the antiproton energy further. The far end of the Penning trap is

at high voltage, and all antiprotons with insufficient kinetic energy to overcome the potential barrier are turned back. A high voltage is put on the window before the antiprotons return to trap them. Once in the trap, the antiprotons are cooled by collisions with electrons that are at the temperature of the trap's walls, typically 4.2 K.

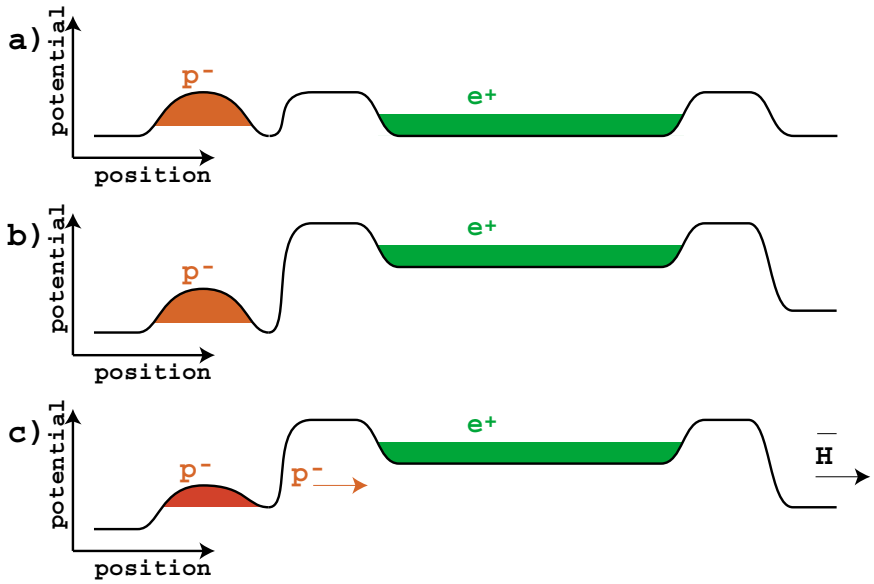

Figure 1: To make a beam of slow antihydrogen, (a) cold antiprotons and positrons are first stored in separate potential wells in a Penning trap. (Because of their negative charge, the potential energy for antiprotons is inverted relative to the electric potential and they can be trapped at peaks in the electric potential.) In (b), a small voltage is applied between the antiprotons and the positrons, so that when the potential barrier confining the antiprotons is lowered in (c), the antiprotons are accelerated and they pass through the positron plasma with their momentum directed down the axis of the trap. If the density of positrons is high enough, some antiprotons will pick up positrons and exit the trap as a beam of slow antihydrogen.

High-density positron plasmas have been produced from radioactive sources by using collisions in a spoiled vacuum to slow the positrons in a trap [12]. The positrons become trapped in regions with better vacuum to reduce annihilation losses as the positrons continue to lose energy through collision in the spoiled vacuum. Accumulated positrons are transferred to a trap with a good vacuum.

When an antiproton enters a positron plasma, it can pick up a positron in a three-body reaction where a second positron carries off the binding energy. The resulting antihydrogen atom, which is in a high Rydberg state, will continue to collide with additional positrons which will change its energy level either up or down. The vast majority of the time the antihydrogen will reionize, but occasionally a collision will put the atom in an energy state where the energy spacing between Rydberg levels exceeds kT, the energy available in a typical collision with a positron. At this point, further collisions will only be able to reduce the energy level and the atom will be stable.

The rate Γ for antiprotons to combine with positrons to become antihydrogen has been calculated [13] to be

$$\Gamma = 6 \times 10^{-13} \left(\frac{4.2}{T}\right)^{9/2} n_e^2$$

where Γ is in inverse seconds, the positron's temperature T is in Kelvin, and the positron density n_e is in cm^{-3}. This means that the half-life for an antiproton to become an antihydrogen in a positron plasma of density $10^8/\mathrm{cm}^3$ is roughly 1 ms at about 140 K.

The method we propose to use to make antihydrogen is to keep the antiprotons and the positrons in separate potential wells inside the same solenoid, as in Figure 1(a). The antiprotons can be released from their well and accelerated by a small voltage to give them a well-defined momentum along the axis of the solenoid (Figure 1(b)). When the antiprotons pass through the positron plasma, some of the antiprotons will acquire positrons and become antihydrogen (Figure 1(c)). Now neutral, the antihydrogen will exit the trap in the direction of the antiproton's momentum. It is likely that using a laser to rapidly de-excite the antihydrogen from its Rydberg state will substantially improve production efficiency.

Antihydrogen made with this technique has the advantage that it is made at a particular time and with a well-controlled velocity. This known time will allow us to measure the speed of the antihydrogen from time-of-flight, and the velocity will allow us to direct the antihydrogen into an apparatus that can measure its gravitational acceleration. However, the finite temperature of the initial antiprotons will result in a spread in both the speed and the direction of the antihydrogen, so it would be quite inefficient simply to try to measure the deflection of the beam due to gravity. Instead, we direct the antihydrogen into an atomic interferometer and measure the gravitational phase shift, as described in the next section.

2.2 The antihydrogen interferometer

An atomic interferometer can be made by placing two identical transmission gratings in the path of an atomic beam. The first grating diffracts the beam into multiple diffraction orders, as shown in Figure 2(a). If the open space in the transmission grating is roughly half the period, then most of the beam will be diffracted into the 0^{th} and $\pm 1^{st}$ diffraction orders, in approximately equal amounts. The second grating splits each of these diffracted beams, causing some of the beams to converge. The converging beams make an interferometer with a Mach-Zender geometry. This is shown by the parallelogram in Figure 2(b), which shows that the -1^{st} diffraction order from the second grating of the $+1^{st}$ diffraction order from the first grating converges with the $+1^{st}$ order from the second grating of the 0^{th} order from the first grating. These beams will recombine at a distance past the second grating equal to the separation between the two gratings. The recombined beams will make an interference pattern with spacing between the peaks equal to the grating period. This spacing is independent of the wavelength because the crossing angle of the beams is determined by the diffraction angle, so longer wavelengths cross at a steeper angle and the distance between peaks is invariant. The diffraction pattern is also independent of the incident direction of the beam on the grating, making this a white-light, extended-source interferometer. Furthermore, because the diffraction pattern matches the grating period, the position of the diffraction pattern can be analyzed with a third transmission grating: more beam will be transmitted when the interference peaks fall on the spaces in the grating than when they fall on the lines. The phase of the interference pattern can be determined by moving the third grating and measuring the transmission.

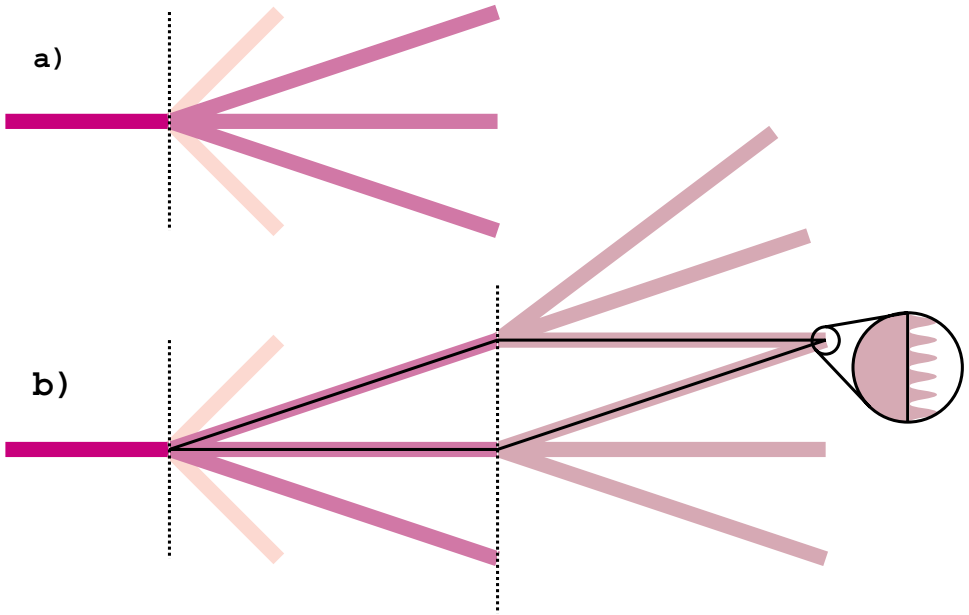

Figure 2: An atomic beam is split by a transmission grating, as shown in (a). If the width of the grating's open spaces is roughly half of the period, then most of the beam will diffract into the 0th order and the $\pm 1^{st}$ orders in approximately equal amounts. A second grating will further split the diffracted beam, and some of the orders will recombine as shown by the parallelogram in (b). This creates a Mach-Zender interferometer geometry. Because the interference pattern has the same period as the gratings that make up the interferometer, a third identical grating can be used to analyze the phase of the interference pattern.

Just such an interferometer has been in use at MIT for some time [14]. This interferometer has been used with a beam of sodium atoms traveling at 1–3 km/s, which have a much smaller wavelength than hydrogen or antihydrogen atoms of the same velocity. The sodium interferometer uses gratings with periods smaller than a micron; with 4000 atoms in the interference pattern it can measure the phase to 0.1 radians or better using a 400 nm period grating.

Gravity causes a phase shift between the beams which results in a shift of the interference pattern. In fact, the pattern shifts by exactly the same amount that individual atoms are deflected by gravity as they traverse the interferometer. For the MIT sodium interferometer, the transmission gratings are mounted with their lines vertical so that there is no gravitational phase shift. However, if the gratings lines are not vertical the gravitational phase shift is an ideal way to measure the gravitational force on the atoms in the interferometer. This is the method we intend to use to measure the gravitational force on antihydrogen.

We can use the performance of the MIT interferometer to estimate how much antihydrogen we will need to make in order to get a useful measurement. Only about 4/9 of the beam making it to the third grating contribute to the interference pattern, and assorted inefficiencies will probably reduce this further by a factor of exactly π. Thus to get 4000 atoms in the interference pattern we will need about 3×10^4 atoms making it to the third grating. Each of the first two gratings will remove about 2/3 of the beam since the gratings require a support structure in addition to their grating lines, so we will need about a quarter million antihydrogen atoms for this particular measurement, which should measure

the gravitational deflection to 15 nm, or better than 1%. A high-precision measurement will require substantially more antihydrogen.

The best way to minimize uncertainties resulting from uncertainties in local g and various lengths in the interferometer is to make a difference measurement between hydrogen and antihydrogen. The leading systematic uncertainty in this difference measurement is likely to result from different beam characteristics (*i.e.* different velocity distributions) or from different detection techniques (antihydrogen is easy to detect when it annihilates). Either of these differences can be largely overcome at the expense of antihydrogen efficiency. Clearly any detection technique that works for hydrogen will also work for antihydrogen, but in general this will not be able to detect as high a percentage of the beam as detecting the annihilation. Similarly, effects from differences in beam characteristics can be reduced by binning the data and comparing like subsamples. The statistical power of the data will be reduced if it is not possible to match all subsamples.

Given that there are many ways to reduce systematic uncertainties (such as varying the length of the interferometer, changing the velocity distributions, etc.), it seems likely that the measurement will be statistics limited for some time. Using a naive scaling from the MIT experiment, we estimate that we should be able to make a difference measurement of better than one part in 10^6 by using 10^{14} antihydrogen atoms, which would represent less than two week's accumulation of antiprotons at current Fermilab stacking rates if there were no losses from transfers or antihydrogen production. Accumulation rates are expected to increase, but at this time there is no way at Fermilab to transfer antiprotons into a trap with high efficiency. We thus expect the measurement to be statistics-limited for some time, but we also expect to be able to improve on the naive scaling to get a more precise measurement from the available antihydrogen.

2.3 The hydrogen interferometer

We are currently building a hydrogen interferometer as a prototype for the antihydrogen device and to demonstrate this technique for measuring the force of gravity. This prototype will give us experience with a hydrogen beam as well as experience with an atomic interferometer. This experience will be valuable because we ultimately want to make a precise difference measurement between matter and antimatter. The experience with the prototype will help us estimate the leading systematic uncertainties in the gravity measurement and how to minimize these uncertainties.

The prototype interferometer uses 1-micron-period transmission gratings mounted at 1-meter spacings, as shown in Figure 3. The gratings are mounted on floating plates that are positioned with piezoelectric actuators. The relative positions of the plates are determined using two systems. The first system uses pattern masks [15] that are projected onto CCD cameras to measure reproducibly the relative alignment of the three gratings. However, this system is fairly slow, so a second system, composed of a pair of optical interferometers, is mounted on either side of the transmission gratings to give a fast measurement of the phase position of the gratings relative to each other. This system is also used with feedback to the piezoelectric positioners to damp vibrations in the system.

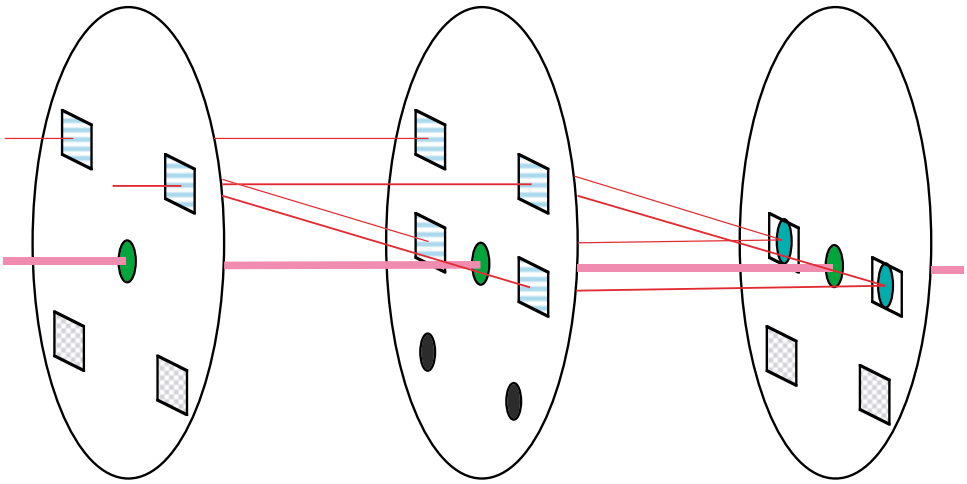

Figure 3: Hydrogen interferometer. The transmission gratings (center) are mounted at 1-meter spacings along with grid projectors and CCD cameras (bottom) for determining relative alignment and a dual laser interferometer system (top and middle sides) for measuring the instantaneous relative phase of the gratings. Only the diffraction orders of the laser beam that interfere are shown.

3 Conclusions

While we know that our understanding of gravity is incomplete, there are very few laboratory experiments we can do to test gravity in new ways that potentially could help our understanding. A direct measurement of the gravitational force on antimatter is one such experiment. A method has been described to make this measurement by directing a beam of antihydrogen through an atomic interferometer and measuring the gravitational phase shift. Going beyond the direct gravitational measurement, an interferometer that precisely measures the difference between hydrogen and antihydrogen could search for a weak fifth force that couples differently to matter and antimatter.

A prototype interferometer is currently being constructed that will measure the gravitational force on hydrogen. This prototype will demonstrate the feasibility of the gravity measurement and the experience with this prototype will help us design an antihydrogen interferometer that minimizes systematic uncertainties.

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