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Letter of Intent: Antimatter Gravity Experiment (AGE) at Fermilab

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Abstract

We propose to make the first direct measurement of the gravitational acceleration of antimatter by taking advantage of Fermilab's unique ability to accumulate large numbers of antiprotons. Such a measurement will be a fundamental test of gravity in a new regime, directly testing both the equivalence principle and the prediction of General Relativity that matter and antimatter behave identically in the gravitational field of the earth. We propose to decelerate antiprotons in the Main Injector and transfer them into an antihydrogen-production Penning trap. The antihydrogen will emerge from the trap in a low-velocity beam.

[1] Also at Muons, Inc.

Initially we will pass this beam through a transmission-grating atomic interferometer where the gravitational deflection will be measured. A 1% measurement should be possible soon after antihydrogen production is established, and a 0.01% measurement should be possible with a few months of dedicated running of the antiproton source after the Tevatron program ends. The low-velocity antihydrogen beam is also ideally suited for use with a new method to slow and trap atoms using magnetic field gradients. With trapped antihydrogen we propose a much more precise measurement using a laser-based interferometry technique to measure any difference between the gravitational forces on matter and antimatter and search sensitively for a possible "fifth force" significantly weaker than gravity. We also anticipate using the trapped antihydrogen for spectroscopy to test CPT with ultra-high precision.

Contents

1 Executive Summary

- Fermilab is at the antiproton intensity frontier, and we propose to use some of these antiprotons to produce a slow antihydrogen beam for making the first direct measurement of the gravitational acceleration of antimatter $\bar{g}$, a key test of the equivalence principle:
  - By using the well-established technology of a transmission-grating interferometer, we can get a quick 1% measurement and ultimately a 10^{-4} measurement of $\bar{g}/g$; and
  - By using hydrogen trapping and cooling techniques currently being developed by collaborator Mark Raizen, we can use a Raman interferometer to measure $\bar{g}/g$ to better than a part per million (possibly much better with enough statistics).
  - We already have some funding for development of the hydrogen trapping and cooling techniques. Two additional NSF proposals are pending which, if funded, would pay for these gravity measurements (but not for the facility; see below).
- Antiprotons can be decelerated in the Main Injector and delivered to a new facility at the end of an existing transfer pipe.
  - Private funding may be available in March to begin construction.
  - Could be ready to receive antiprotons in calendar 2009.
  - Could use Recovery Act funding if available and private funding is delayed.
  - Minimal impact on existing physics program for initial work. Ultimate precision would require dedicated running of the antiproton source.
- Antiprotons will be captured in a Penning trap.
  - We will use NASA's existing HiPAT trap.
  - Capture efficiency will approach unity when using new deceleration ring.
    - ∗ If ring is based upon surplus SLAC magnets, could be ready mid-2010.
    - ∗ If new magnets are needed, would be funded in 3rd year of private funding.
  - Until deceleration ring complete, we can slow antiprotons by using dE/dx in a degrader.
    - ∗ Efficiency for a simple degrader is about 10^{-6}.
    - ∗ By using a reverse linac after degrader, efficiency $> 10^{-4}$.
      - · Antiprotons from 5 hours of stacking needed for a 1% measurement.
    - ∗ Which technique we use will be determined by ring schedule.

2 Motivation

Most physicists expect the gravitational acceleration of antimatter to be identical to that of matter, but the question has not been directly tested by experiment. The theory of General Relativity (GR) is based on the equivalence principle, which implies that the gravitational acceleration of any object is independent of the object's composition. This principle has been verified to high precision with matter. However, proposed quantum theories of gravity generally include non-tensor terms that can violate the equivalence principle and/or the inverse-square dependence on distance [1]. Measurement of the acceleration of antimatter in the Earth's gravitational field is a new way to test for such effects. For example, hitherto unknown weak vector- and scalar-mediated forces could cancel for matter-matter interactions but add for matter-antimatter interactions [1]. Even if this measurement confirms the predictions of GR, it would extend the equivalence principle to antimatter and would be a classic test of General Relativity, "one for the textbooks."

To date, direct measurements have not even ruled out the possibility that antimatter in the gravitational field of the earth will rise rather than fall. As remote as the possibility may seem, this "antigravity" scenario has been considered in the literature, including the observation that it could provide an explanation for the observed cosmic baryon asymmetry [2], and even a possible role in dark energy has been suggested [3]. (This mechanism was considered by P. Morrison [2], as well as others, before CP violation was discovered and suggested by Sakharov as the likely solution to the baryon asymmetry problem; see also R. W. Brown and F. W. Stecker [4], who consider it in the context of Grand Unified Theories.) While K^0 mixing might suggest that the gravitational interactions of matter with matter are identical to those with antimatter to high precision [5, 6], it has also been argued that the observed K^0 CP violation could be a consequence of gravitational repulsion between quarks and antiquarks [3, 6]. These papers identify antimatter with the repulsive solutions to the Kerr-Newmann equation, thus raising the possibility for antigravity within General Relativity.

In the end, the best way to determine the gravitational force on antimatter is by direct measurement. We are proposing to do this at Fermilab, in the near future and at modest cost.

3 Methods

We are pursuing two methods for measuring the gravitational acceleration of antimatter, $\bar{g}$. The first method uses a transmission-grating interferometer [7, 8] and is capable of measuring $\bar{g}$ with a precision of better than $g/10^4$ because the phase shift of the micron-scale interference pattern is proportional to the gravitational deflection of the beam. This method makes efficient use of a slow antihydrogen beam and does not require trapping the antihydrogen. All the technology needed for this measurement has been demonstrated in other contexts and this technique will work with antihydrogen in any atomic state, so this method minimizes technical risk and should allow us to make the first measurement of $\bar{g}$ soon after antihydrogen production is established. The second method uses a Raman interferometer to measure $\bar{g}$. Here the antihydrogen beam is decelerated with magnetic gradients and trapped. The trapped atomic wave packet is split in the vertical direction and then recombined with a series of laser pulses. This method is capable of measuring $\bar{g}$ with a precision better than $g/10^9$. Details of antihydrogen production and the interferometers are discussed below.

3.1 Transmission-Grating Interferometer

The most obvious method to measure $\bar{g}$ using the antihydrogen beam would be to collimate the beam to make it narrow in the vertical direction and measure its position after it had propagated a sufficient distance within a drift tube. However, this method would make inefficient use of the antihydrogen. A more efficient measurement can be made using an interferometer. The concept is to set up an interference pattern with a pair of diffraction gratings, and to measure the phase of the interference pattern with a third grating. The phase shift caused by gravitation can be measured by comparing the phase shifts for beams of differing velocities. The axis of the interferometer can also be rotated about the beam axis; when the grating lines are vertical gravity will not affect the interference pattern.

Perhaps the ideal interferometer for this experiment is a configuration that has been used for both neutron and atom interferometry [9, 10] (Figure 1). This interferometer consists of three equally spaced transmission gratings, each with identical line spacing. The first two gratings set up an interference pattern that is independent of both the wavelength and the spatial coherence of the source [11] (a "white light, extended source" interferometer). This interference pattern has a spatial period equal to the line spacing of the gratings, so the phase of the interference pattern can be analyzed by using a third identical grating as a mask and measuring the transmission as a function of the mask's position. The interference pattern is localized in x (the direction perpendicular to the grating planes), so while the distance between the first and second gratings is arbitrary, the distance from the second to the third grating must match the distance between the first and second gratings. A diagram illustrating the principle of the interferometer is shown in Figure 2 and an example interference pattern is shown in Figure 3.

Not all of the diffraction orders from the first two gratings will contribute to the interference pattern. However, by using gratings with 50% transmission (i.e., the slit width is half of the grating period), the even diffraction orders are suppressed, and most of the transmitted beam appears in the 0^{th} and $\pm 1^{st}$ orders in approximately equal amounts. The orders that will interfere are shown in Figure 2. Ideally, 4/9 of the beam transmitted through the second grating (four of the nine principle diffraction orders) will contribute to the interference pattern.

The phase of the interference pattern can be measured by moving the third grating in the y direction. The transmission is then recorded as a function of the phase of the grating: the transmission is highest when the interference peaks fall on the slits.

The interference pattern shift is proportional to the amount by which transmitted

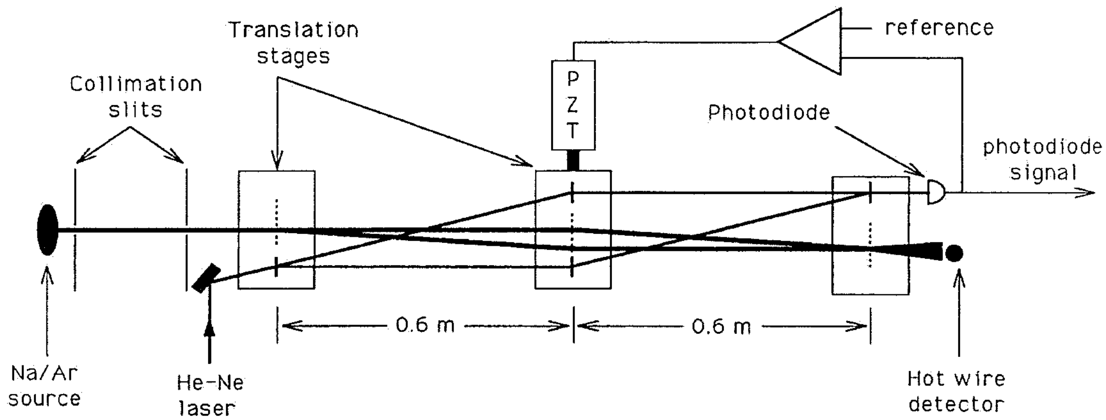

Figure 1: Schematic of the sodium-atom interferometer in use at MIT. A similar interferometer can be used with antihydrogen to measure the gravitational force on antimatter. Separated beams are not needed for the gravity measurement, so the collimator is unnecessary (thus making more efficient use of the antihydrogen) and the period of the diffraction gratings can be much larger (making construction and alignment much easier). (From reference [9].)

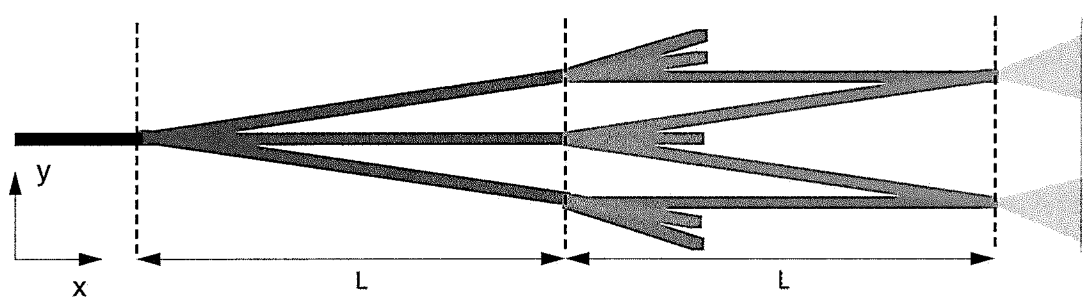

Figure 2: Principle of three-grating interferometer for measuring $\bar{g}$. The three diffraction orders shown will contain most of the transmitted beam in approximately equal amounts. The orders that are drawn to the third grating cause an interference pattern with a frequency that matches the grating's line spacing. The diffraction orders that are not followed to the third grating do not contribute to this pattern, but rather cause a flat background.

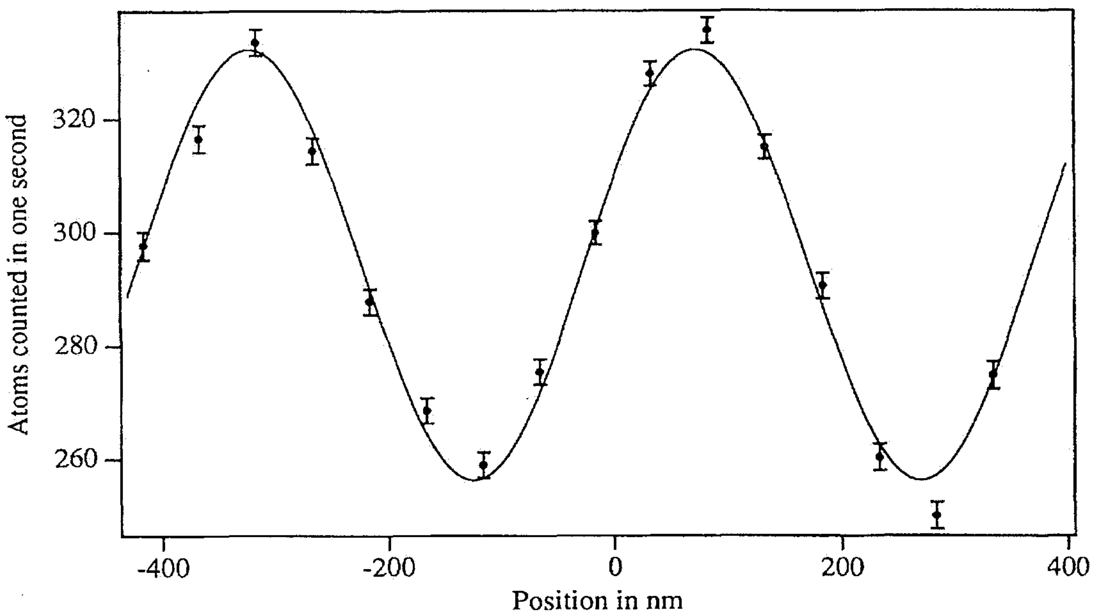

Figure 3: Interference pattern measured using sodium atoms in the MIT interferometer from 400 seconds of data; note suppressed zero. (From reference [9].)

atoms are deflected while transversing the interferometer. Thus, for deflection D given by

$$D = \bar{g}\frac{L^2}{v^2}, \tag{1}$$

where L is the separation between successive gratings and v is the velocity of the antihydrogen, the resulting phase shift $\Delta\phi$ is

$$\Delta\phi = 2\pi D/d, \tag{2}$$

where d is the line spacing of the grating. It is important to note that while the interference pattern is independent of velocity (wavelength), the deflection (or equivalently the phase shift) due to gravity is not. Thus, when the phase shift due to gravity becomes significant, a large velocity dispersion can wash out the interference pattern, so the beam used to make this measurement must either have a sufficiently small velocity dispersion, or else the velocity of each antihydrogen atom must be measured.

Atomic interferometers used with matter beams are a mature technology which is discussed in detail by our Univ. of Arizona collaborator Alexander Cronin in [12]. In general, atom interferometers are oriented with the grating lines vertical in order to avoid gravitational phase shifts, and the gratings are moved to evaluate the phase of the interference pattern. For the gravity measurement, the gratings would be oriented horizontally and the phase would be measured as a function of the time-of-flight (TOF) since the gravitational phase shift is a function of the length of time the beam takes to traverse the interferometer. Figure 4 shows a simulation of the TOF dependence of

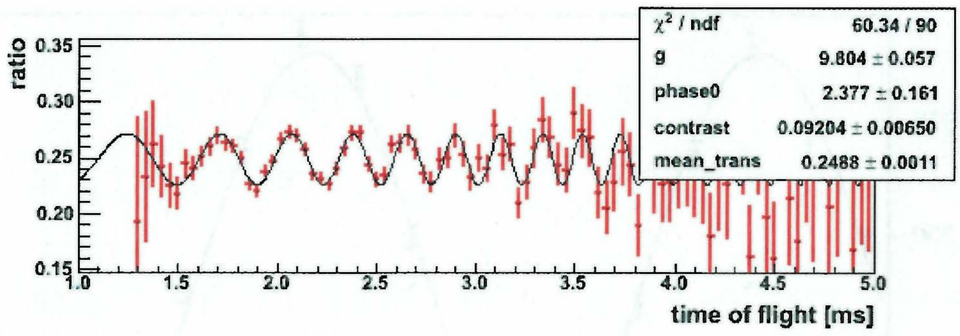

Figure 4: Ratio of number of antihydrogen atoms exiting interferometer to those reaching 3rd grating vs. time-of-flight; fit shows 0.6% measurement of $\bar{g}$ with 1 million atoms incident on 1st grating (3-grating Mach-Zehnder-interferometer Monte Carlo simulation by G. Horton-Smith of Kansas State Univ.); grating period = $1\,\mu$m, average $\overline{\mathrm{H}}$ velocity = $1\,$km/s, $T = 4\,$K.

the fraction of $\overline{\mathrm{H}}$ atoms emerging from the 3rd grating; an r.m.s. error of 0.6% of $\bar{g}$ is achieved with 1 million atoms incident upon the interferometer.

We require the vertical noise motion of the interferometer to be small compared to a grating period over the flight time of the antihydrogen in the interferometer, which is of order 1 ms. RMS noise with an amplitude of 10% of the grating period would reduce the interference contrast by only about 1% which would be acceptable. Typical seismic noise peaks at $1\,\mu$m (RMS)/$\sqrt{\mathrm{Hz}}$ at 0.1 Hz, falling exponentially to $1\,$nm/$\sqrt{\mathrm{Hz}}$ at 1 Hz, beyond which it remains flat to 10 Hz. It then falls as $1/f^2$ at higher frequencies, so seismic noise is well below the level of concern. On the other hand, some laboratory equipment such as turbo pumps vibrate at problematic frequencies, so we need acoustic isolation.

Suspending the interferometer support tube on 30-cm-long steel wires, sized to be stressed to 30% of yield tension, will yield a vertical bounce resonance of about 10 Hz. This forms an accoustic low pass filter ($1/f^2$), with about 10^{-2} rejection at 100 Hz and 10^{-4} at 1 kHz, adequate to suppress vertical motion for a 10^{-4} gravity experiment. Horizontal motions are more suppressed due to the lower pendulum resonance of about 1 Hz. Further vertical isolation can be achieved by suspending the wires from blade springs, lowering the resonance to about 1 Hz. Still further isolation can be had by mounting the entire assembly on spring supported massive steel blocks, but this is almost surely not necessary. Gustafson (University of Michigan) will take responsibility for vibration isolation, monitoring, and simulation, based on his experience in LIGO.

While antihydrogen is electrically neutral, it is still subject to electromagnetic forces from field gradients, particularly for atoms in Rydberg states. Both electric and magnetic fields can be shielded by the pipe used to support the grating plates, which will be plated with gold on its interior surface. In the current design, the beam would be at least 7.5 cm from the support pipe, which will limit the maximum field gradients

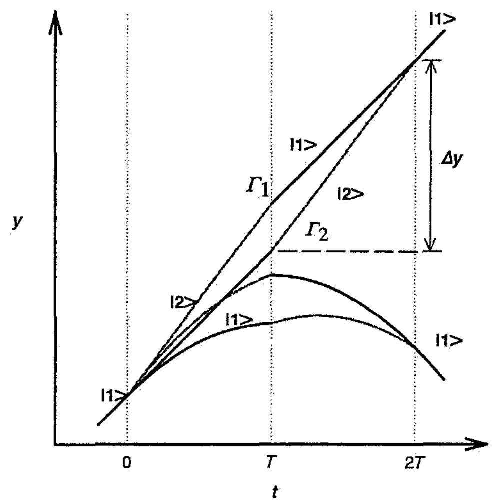

Figure 5: Phase space diagrams, in the presence and absence of gravity, for atom interferometer based upon $\frac{1}{2}\pi - \pi - \frac{1}{2}\pi$ pulse sequence. The first laser pulse at $t = 0$ splits the atoms into superpositions of two momentum states which separate spatially. The second pulse at $t = T$ brings these split states back together, and the third pulse at $t = 2T$ recombines them with a phase shift that depends upon local g. (After reference [13].)

since they fall off with a high power of distance. Note that there will necessarily be substantial field gradients as the antihydrogen exit the Penning trap, but these do not affect the gravity measurement. The only field gradients that are relevant to the gravity measurement are those between the gratings of the interferometer. We will take three approaches to limiting the effects of stray fields on the gravity measurement: shielding and measuring the stray fields, making the antihydrogen as tightly bound as possible, and eliminating the remaining high Rydberg states from the beam.

3.2 Raman Interferometer

High-precision measurements of the local gravitational acceleration g have been made by Chu *et al.* [13] using an atomic Raman interferometer. They have measured local g to better than one part in 10^{10}. The same technique can be used with hydrogen and antihydrogen to measure $\bar{g}$.

The principle of the interferometer, illustrated in Figure 5, is to use two ground state hyperfine levels of an atom and to drive two-photon stimulated Raman transitions between those states by tuning the frequency difference between the lasers to match the hyperfine splitting. The configuration of counter-propagating beams for the Raman transition maximizes Doppler sensitivity, and the use of $m = 0$ magnetic sublevels minimizes the effect of stray magnetic fields. The geometry for gravity measurements is such that the two Raman beams are aligned along the vertical direction. The first step is to excite the 1S state with a two-photon transition at 243 nm to drive the atoms to the metastable 2S state. The lifetime of that state (120 ms) is long enough to enable a precision measurement. The Raman laser beams will be tuned about 20 GHz from the 2S–3P transition near 657 nm. Both lasers (243 nm and 657 nm) will be all-solid state and are being developed by University of Texas collaborator Mark Raizen's group. A sequence of three pulses will split and recombine the atomic wavepackets in the vertical direction. The sensitivity of the Raman interferometer depends on the accumulated phase shift during the free propagation time t between pulses, and scales as t^2, which emphasizes the importance of an ultracold sample in order to enable long interaction times. The signal-to-noise ratio scales with only the inverse square root of the number of atoms, so it is relatively insensitive to statistics as compared with the effect of the interaction time. A comparative measurement of $\bar{g}/g$ with this method could be at the level of one part per billion or better.

Measuring $\bar{g}$ with this Raman interferometer requires trapping and cooling of the antihydrogen. Trapping and cooling of atoms in the gas phase has been a major area of research for over thirty years [14]. The advances in this field were enabled by laser cooling, which was recognized by a Nobel Prize in Physics in 1997. Despite the enormous success of this method, its application has so far been limited to only a small fraction of the periodic table. The reason for the limited applicability of laser cooling is that it requires a two-level cycling transition and one that is accessible with stabilized lasers. These constraints have excluded most of the periodic table as well as all molecules. In particular, laser cooling of hydrogen has not been possible. Magnetic trapping and evaporative cooling of hydrogen was accomplished by Kleppner and Greytak [15] but required a complex dilution refrigerator, and could not be extended to D or T.

In the past few years, the Raizen group at the University of Texas at Austin has pioneered a simple two-step approach to trapping and cooling that will work on any paramagnetic atom or molecule. This includes most of the periodic table (about 95% in the ground and first metastable states) as well as many molecules. The first step, the atomic coilgun, uses pulsed magnetic fields to stop atoms. The second step, single-photon cooling, uses the information carried off by one spontaneously scattered photon per atom to further cool them. This method is a direct realization of a proposal by L. Szilard from 1929 in an effort to resolve the paradox of Maxwell's demon in terms of information entropy. These new approaches are currently being refined by the Raizen group and applied to hydrogenic atoms H, D, and T. The same methods will also work for antihydrogen and will enable a breakthrough in fundamental tests with neutral antimatter.

The Raizen group proposed that paramagnetic atoms in a beam could be stopped using a series of pulsed electromagnetic coils [16]. The principle of magnetic deceleration is conceptually simple: low-field seekers lose kinetic energy by moving into the high magnetic field region at the center of an electromagnetic coil. When the atom reaches the top of the "magnetic hill" the magnetic field is suddenly switched off. Due to conservation of energy, the amount of kinetic energy lost is equal to the Zeeman

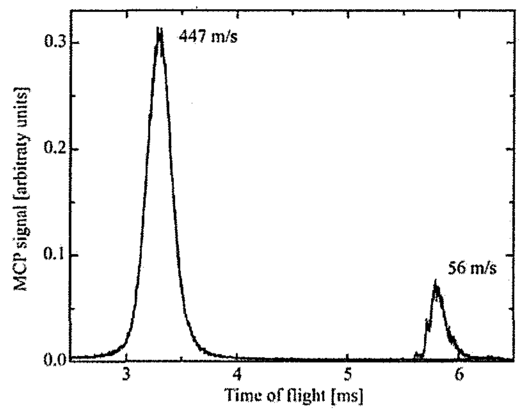

Figure 6: Magnetic slowing of a supersonic beam of metastable neon with an atomic coilgun. The final velocity was needed to extract the atoms to a detector, and over 99% of the initial kinetic energy is removed from the beam. Stopping the neon would have been possible, but would have required a different detection mechanism. From ref. [17].

energy shift,

$$\Delta E = g_s \mu_\beta M_J H \tag{3}$$

where g_s is the Landé factor, μ_β is the Bohr magneton, M_J is the projection of the total angular momentum on the quantization axis and H is the magnetic field strength. In the ideal operation of the atomic coilgun, the velocity distribution of the atoms is not changed, but the mean velocity in the laboratory frame is removed. This is therefore not a cooling process, simply a translation in velocity space. The magnetic stopping is overall quite robust as low-field seeking states are guided transversely along the axis and not lost from the beam. Longitudinal bunching is accomplished by timing to ensure that the atoms are confined in a magnetic valley that is decelerating. After stopping the atoms, they can be confined in a magnetic trap. The coilgun has been implemented experimentally, and a beam of metastable neon (see Fig. 6) as well as a beam of molecular oxygen have been stopped by the Raizen group [17, 18]. Parallel work by the Merkt group (ETH Zurich) has stopped hydrogen [19–21].

The next step is to cool the atoms further, and this is where the method of single-photon cooling comes in. The basic construction is a one-way barrier for atoms as proposed in 2005 by Raizen and collaborators [22]. The experimental implementation was carried out using a hybrid magnetic and optical trap with atomic rubidium [23]. A phase space enhancement of 350x was reported, although less than 1% of the atoms were captured in an optical tweezer [24]. A new version of single-photon cooling is an all-magnetic approach with dressed RF states and a single laser beam to induce the irreversible step needed for cooling [25]. This version will enable trapping of nearly all the atoms, limited only by the branching ratio of the spontaneously emitted photons (around 50% of the atoms can be trapped after emission of the photon). This method will work well on any multi-level atom or molecule, and in particular will work on hydrogen. In that case, a laser at 243 nm will drive the two-photon 1S-2S transition which will be quenched to emit a Lyman alpha photon at 121 nm. Trapping and cooling of hydrogen, deuterium, and tritium are in progress in the Raizen lab and should be working within the coming year. It appears feasible to reach a phase space density that will enable rapid evaporative cooling to quantum degeneracy (a Bose-Einstein condensation) for hydrogen and tritium. The next step will be to use the trapped ultracold tritium atoms for a possible determination of the neutrino rest mass [26].

The gravity measurement could be first demonstrated with hydrogen thereby proving the capability with antihydrogen. In particular, the deceleration and trapping of hydrogen will provide an extremely sensitive trace-hydrogen detector, so it will allow the antihydrogen production trap to be commissioned and optimized with hydrogen production. Since this is likely to be the most challenging aspect of the experiment, the ability to measure hydrogen production will greatly assist the commissioning of the experiment.

There will undoubtedly be optimum operating conditions for the protons and electrons in order to maximize the hydrogen-beam brightness. This includes the density and temperature, but can have other aspects as well. For example one important point is that the hydrogen atoms will be created in high-lying Rydberg states. Calculations by Robicheaux [27] and independently by Pohl *et al.* [28] have shown that trapped H-bars will undergo significant translational cooling as they cascade down to the internal ground state. This same mechanism could be used to cool the beam of antihydrogen as they are launched out of the Penning trap, and would require a magnetic field minimum along the axis of propagation.

Although not the main objective of this LoI, it is worth noting that a trapped sample of antihydrogen also lends itself naturally to a precision spectroscopic measurement of the 1S-2S transition. The Raizen group is already planning such measurements on trapped atomic tritium and will collaborate with James Bergquist (NIST) and Jun Ye (JILA), two of the world's experts on ultrasensitive spectroscopy. Towards this goal, they will stabilize the 243 nm laser to the required linewidth, and also use a laser tweezer near 515 nm inside a power build-up cavity to hold the atoms as they are being probed. This wavelength ensures that the optical dipole shift of the 1S and 2S states are identical, a so-called magic wavelength that is used in atomic lattice clocks. A spectroscopic comparison between hydrogen and antihydrogen could be done at the part in 10^{18} level.

3.3 Low-Energy Antimatter

Antiprotons from Fermilab's antiproton source can be decelerated in the Main Injector and transferred to a new experimental enclosure at MI-9. Such operation has been previously discussed by Jackson [29], and some planning and partial construction for it has already occurred. Plans for the enclosure are shown in Figure 7. Deceleration of

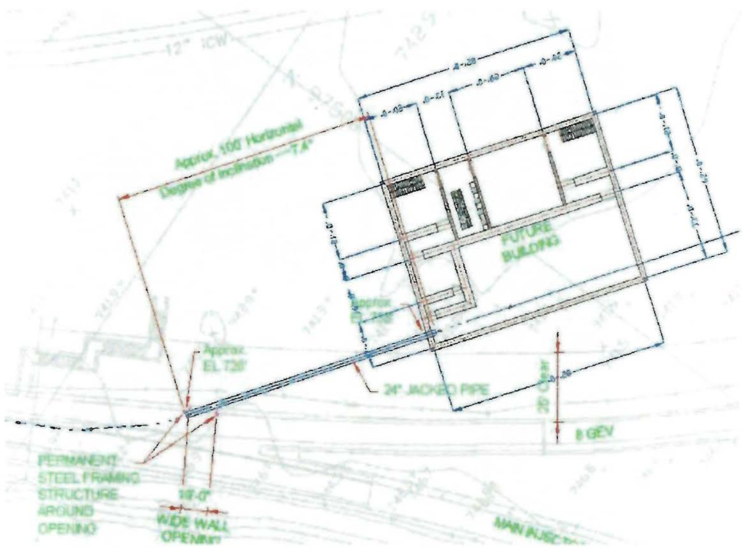

Figure 7: Design for an experimental enclosure to be built at MI-9 to house experiments using low-energy and trapped antiprotons.

protons in the Main Injector has already been demonstrated to 3 GeV/c [30]. Demonstrating that the Main Injector magnets can ramp down to 2 GeV/c was accomplished during the same studies, and an advancement in RF technology developed by Hbar Technologies, LLC [31] now makes deceleration of antiprotons down to 1 GeV/c possible with existing FNAL infrastructure. Studies of deceleration ramps can be done without beam in the Main Injector, and six 4-hour study periods with a proton beam are sufficient to determine whether 1 GeV/c (or lower) is achievable.

Antiprotons decelerated in the Main Injector can be extracted "up" the Main Injector proton injection line. A needed switching magnet (to prevent the decelerated antiproton bunch from proceeding back into the Booster, and instead divert it to a new MI-9 transfer line to be built) has been designed for this purpose and assembled by Hbar Technologies, LLC. A carrier pipe, shown in Figure 8, has already been installed for this low-energy transfer line to bring the antiprotons to the new experimental enclosure to be built at MI-9. A deceleration ring employing stochastic cooling is planned for the enclosure that will allow nearly all of the antiprotons to be trapped in a Penning trap. It may be possible to use surplus magnets from SLAC for this ring, in which case the ring could be completed as early as summer 2010. If these magnets cannot be used, new magnets would be built based upon the design used for a ring at the Indiana University Cyclotron Facility (IUCF).

Until the deceleration ring is operational we can trap antiprotons by using a degrader to reduce their energy. A simple degrader will give a trapping efficiency of 10^{-6} into a trap with 20 keV electrodes. This efficiency can be increased substantially by using a reverse linac that switches the voltage on a series of electrodes at the appro-

Figure 8: End of carrier pipe where it penetrates the wall of the Main Injector tunnel. This pipe was installed to enclose a low-energy beamline from the Main Injector at MI-10 to the experimental hall at MI-9. The four penetrations on the ceiling also lead to the location of the future MI-9 enclosure.

priate times. We have simulated a design that can capture antiprotons up to 3 MeV and has a capture efficiency of 10^{-4}. The efficiency can be further improved by using phase-space rotation techniques, for example by swapping momentum spread for transverse emittance. This can improve the trapping efficiency by at least another factor of five and probably significantly more. Whether or not we need to employ these techniques will depend upon the relative schedules of the experiment and the deceleration ring. Since the ring may be able to use surplus magnets, it could be built quite rapidly in which case high-efficiency transfers to the trap will be available by the time the experiment is ready for high-statistics measurements. On the other hand, if the experiment is proceeding more rapidly than the deceleration ring, we will invest some effort into optimizing the trapping efficiency. Given the large number of antiprotons available at Fermilab, even the baseline trapping efficiency is adequate for making first measurements. With a capture efficiency of 10^{-4}, only 5 hours of stacking time is needed to produce enough antiprotons for the 0.6% measurement shown in Figure 4 assuming that only 1% of the antiprotons are made into antihydrogen that enter the interferometer.

Once in a Penning trap, antiprotons are easily cooled to cryogenic temperatures by electrons in the trap. The electrons cool by synchrotron radiation to the temperature of the trap walls, and the antiprotons are cooled by collisions with the electrons [32].

As soon as we have funding, NASA will ship their High Performance Antiproton Trap (HiPAT) and related equipment, shown in Figures 9 and 10, to HBar Technologies. This trap will be used for the gravity measurement. The existing HiPAT cryostat is already configured to meet the needs of the experiment. The H^- and proton sources and associated optics are also already configured to commission the experiment. Some modification to the existing electrode structure will be needed for the initial commissioning of the experiment, and we anticipate that a new electrode structure optimized for low-velocity antihydrogen formation will be built. The new structure will be housed in a vacuum pipe with ends that mate to gate valves and include non-intercepting vacuum connections that allow antiproton injection from one end and antihydrogen emission from the other end. We also have access to a second NASA solenoid with a higher field and a larger bore. This magnet will be used for the initial trapping and cooling of the antiprotons.

To make antihydrogen, positrons are needed in addition to antiprotons. Positrons with the needed parameters can be accumulated from a ^{22}Na source using apparatus that is now commercially available [33]. This source, shown in Figure 11, can provide 8×10^6 positrons/sec from a 50 mCi ^{22}Na source. The positrons are accumulated in a trap using a differentially pumped spoiled vacuum [34]. The ATHENA collaboration has used this technique to achieve positron densities of $2.6 \times 10^{10}/\text{cm}^3$ [35]. We should note that the commercial supplier of ^{22}Na sources has been revamping its production line, so new sources are not currently available. Production is expected to resume this April, but because of their order backlog it will probably be a year before we will be able to obtain a ^{22}Na source.

3.4 Antihydrogen Production

Formation of antihydrogen has been pioneered by the ATHENA [36] and ATRAP [37] groups at the CERN AD. The primary goal of these groups has been to trap antihydrogen in order to perform spectroscopy for high-precision CPT tests, so they are attempting to produce antihydrogen with extremely low velocity in order to trap it. They produce antihydrogen by trapping cold antiprotons and positrons in adjacent potential wells in a Penning trap and causing the antiprotons to overlap with the positron plasma.

Figure 12 shows the velocity distribution of antihydrogen produced in ATRAP [38]. In this experiment the antihydrogen was made in a beam along the axis of the trap by gently heating the antiprotons so that they pass through the positron plasma. The low-velocity peak corresponds to the energy given the antiprotons, while the long, high-velocity tail is believed to come from charge exchange of these low-velocity antihydrogen atoms with hot antiprotons in side wells of the trap [38]. The low-velocity peak is in the proper range for use in a gravity measurement, while the high-velocity tail could be used to monitor the alignment and phase of the interferometer gratings. The relative size of the tail could be reduced by reducing the number of hot antiprotons in side wells.

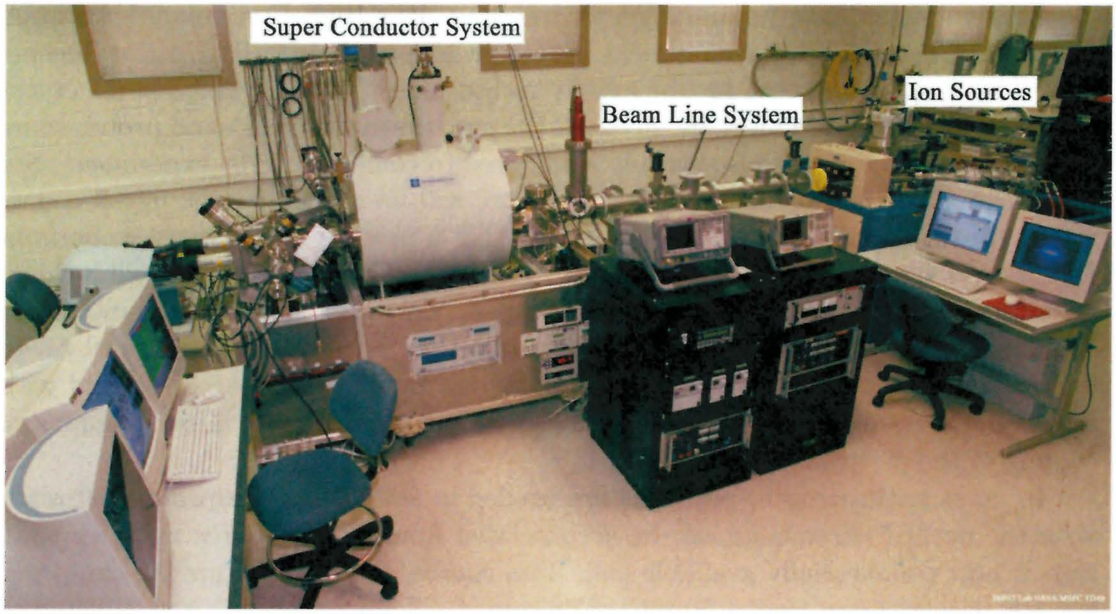

Figure 9: NASA's High Performance Antiproton Trap (HiPAT), which will be used for the Antimatter Gravity Experiment.

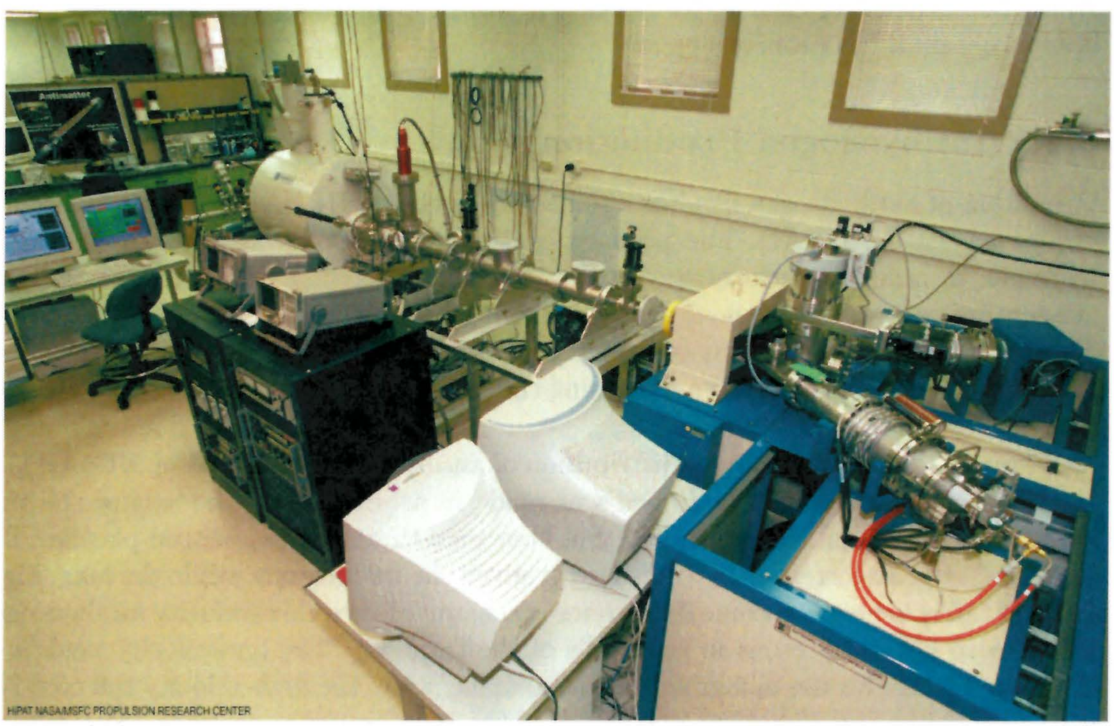

Figure 10: Ion sources for HiPAT.

Figure 11: A commercially available positron source [33].

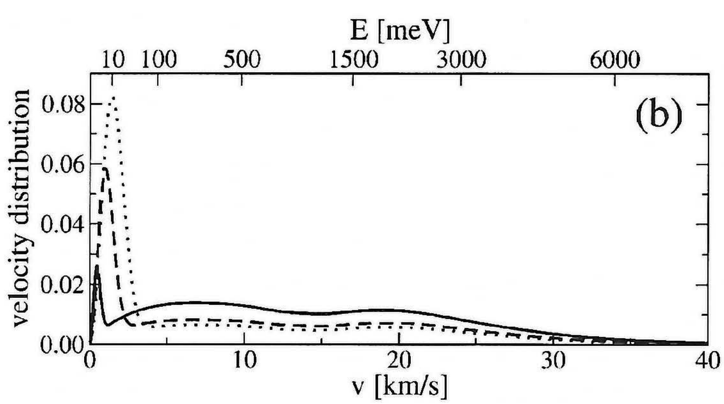

Figure 12: The velocity distribution of antihydrogen produced by the ATRAP collaboration. The three curves are for average antiproton velocities corresponding to $K_B T_{\bar{p}} =$ 1 meV (solid), 2 meV (dashed), and 5 meV (dotted). The long, high-velocity tail is believed to come from antihydrogen atoms that charge-exchange with hot antiprotons in side wells of the trap. (From reference [38].)

The antihydrogen beam produced by the ATRAP collaboration can be considered proof that it is possible to produce a beam of antihydrogen with the right characteristics for the gravity measurement. However, it would be necessary to measure the velocity of each antihydrogen atom that traversed the interferometer in order to resolve the interference pattern and measure the gravitational deflection. This would require chopping the beam and making a time-of-flight measurement for each antihydrogen atom that passed through the interferometer.

While this baseline design would clearly work, it would make inefficient use of the antihydrogen produced. An improvement on this design that we will pursue is to keep the positrons and the antiprotons separated, and then the antiprotons will be accelerated by a small voltage pulse to a velocity of about a km/sec before they pass through the positron plasma (see Figure 13). The time of the pulse will provide a start time for the time-of-flight measurement. Some of the antiprotons will pick up positrons to become antihydrogen, which will exit the trap in the direction of the antiproton's momentum, while the rest will remain trapped for another pass. The rate for antihydrogen production in a strong magnetic field by the three-body reaction $\overline{p} + 2e^+ \rightarrow \overline{\mathrm{H}} + e^+$ has been calculated [39] to be

$$\Gamma = 6 \times 10^{-13} \left(\frac{4.2}{T}\right)^{9/2} n_e^2 \, [\mathrm{s}^{-1}] \tag{4}$$

per antiproton, where T is the absolute temperature and n_e is the positron density per cm^3. For example, with conservative values of $n_e > 10^8/\mathrm{cm}^3$ at a temperature of 4.2 K, each antiproton has a 45% chance of becoming an antihydrogen on a single pass through a 10-cm-long positron plasma at 1 km/s. This calculation assumes an infinite magnetic field, and more recent calculations [40] indicate that the rate is higher with a finite magnetic field, and that the rate does not fall off at higher temperatures as rapidly as this calculation indicates. Also, this calculation neglects radiative combination and the three-body reaction $2\overline{p} + e^+ \rightarrow \overline{\mathrm{H}} + \overline{p}$, which should enhance the production rate for the high antiproton densities achievable at Fermilab.

High positron densities can be achieved by compressing the positrons radially with a rotating electric field [41]. It should be possible to convert nearly all antiprotons that enter this high-density positron region into antihydrogen on a single pass. The antiprotons at other radii that are not converted into antihydrogen remain trapped, so we would incorporate multiple passes to increase the efficiency of antihydrogen production. We note that ATRAP [42] and ATHENA [43] observe substantial antihydrogen production rates and are able to convert a significant fraction (>10%) of their trapped antiprotons into antihydrogen.

We plan to explore ways of extracting antiprotons from a limited part of phase space in order to make an antihydrogen beam with smaller emittance. This is similar to the way antiprotons are extracted for Tevatron shots. An example would be to turn off the "barrier" electrode that keeps trapped antiprotons from entering the positron plasma in an adjacent potential well, and to confine the antiprotons with a magnetic pinch mirror instead. This mirror is leaky, but the antiprotons that leak are the ones

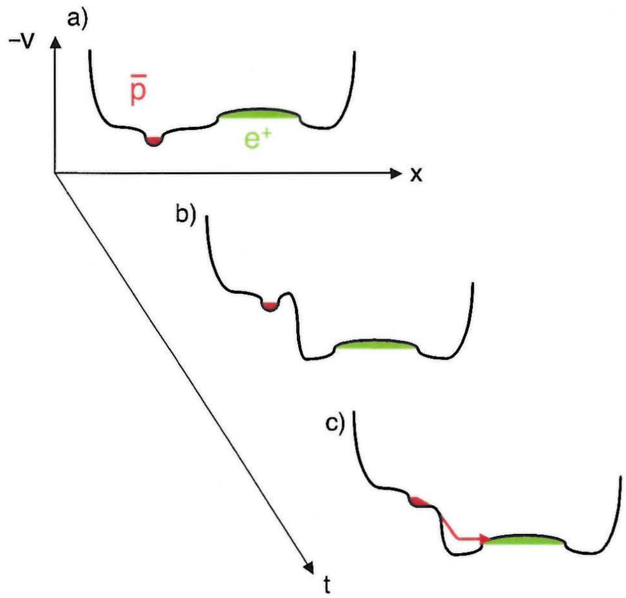

Figure 13: Cartoon of a) trap potential vs x at $t = 0$ showing antiprotons (red) and positrons (green) in separate wells (note that due to their opposite charges they are portrayed as sitting "above" and "under" their wells, respectively); b) and c) are snapshots showing voltage manipulations to accelerate the antiprotons such that they pass through the positrons: at time b), the $\bar{p}$ well potential is "raised" (made more negative) in preparation for $\bar{p}$ acceleration; at time c), the potential barrier between the $\bar{p}$ and e^+ wells is dropped and the $\bar{p}$'s are accelerated through the e^+ well. Our studies indicate that a pulsed voltage used to kick the antiprotons would give a shorter pulse than simply dropping the potential barrier. Additionally, we will explore techniques for extracting a limited phase space from the antiproton plasma in order to produce a higher-quality antihydrogen beam.

on axis having very little cyclotron motion, precisely the ones we want to extract to make the highest quality antihydrogen beam.

The beam characteristics required for the atomic interferometer are similar but not identical to those required for the coil gun used to slow the antihydrogen for trapping. Both applications require a pulse of antihydrogen generated at a known time and both will have a limited transverse acceptance, so we may implement an ionizing collimator to recover the antiprotons from antihydrogen produced with large transverse velocity. The main difference between the beams is that the atomic interferometer can make use of a very large spread of antihydrogen velocities, whereas the coil gun will only accept a limited range of velocities. The thermal velocity of antiprotons at 4 K is significant compared to the velocity of the beam, so we will need to either select a limited phase space from the antiprotons or ionize antihydrogen produced outside the acceptance window in order to make efficient use of the antiprotons. Fortunately, we have plenty of handles we can use to optimize the beam characteristics.

3.5 Antihydrogen Detection

Detection of antihydrogen is straightforward and can be accomplished with little background [37,44,45], especially considering that we will be detecting the antihydrogen a substantial distance away from the stored antiprotons. We have simulated a scheme involving two barrels of scintillation counters, one surrounding the 3rd grating and the other surrounding a thin disk of material in which antihydrogen atoms emerging from the interferometer annihilate. We find that events can be unambiguously detected, with over 99% efficiency and less than 0.1% fake rate.

We are considering a baseline detector system utilizing scintillator bars available at Fermilab as surplus from the KTeV experiment. Assembly of the detector will require the building of a frame and its operation will require electronics that we expect to be available at Fermilab. The construction of the detector, to be built almost entirely of spare/surplus equipment, is expected to be of minimal cost.

We are investigating the possibility of using a small-diameter scintillating-fiber barrel tracker inside the vacuum system as an alternative to an external scintillator array. The barrel would be placed between the third grating and the annihilator, and with as few as two layers would allow us to distinguish between antihydrogen atoms that are transmitted and those that annihilate on the third grating. Since the third grating is being used as a mask, recording annihilations on the third grating as well as annihilations from transmitted antihydrogen will increase the statistical precision of the measurement by a factor of $\sqrt{2}$.

While not absolutely necessary, it would be useful to know the transverse position of each annihilation to monitor the grating alignment and to correct for any imperfections in the gratings. One method for finding the annihilation position would be to annihilate the antiprotons on the same MCP we use to detect the matter beam when calibrating the interferometer (see Section 3.6). ASACUSA has used an MCP to detect ultra-slow antiprotons [46]. They find a substantial amount of charge is recorded as a result of the antiproton annihilation, so we are confident that we will be able to use an MCP to detect antihydrogen.

3.6 Calibration

Making a precision measurement of $\bar{g}$ will require careful attention to the calibration of the interferometer. This will be done by measuring g for a matter beam in the same apparatus. We will investigate beams that can be created in a manner that does not interfere with the antihydrogen production apparatus so that the matter beam can be run with a minimum of changes to the equipment. If possible, we will make measurements will several different matter beams to help quantify our systematic uncertainties.

The baseline plan is to use a beam of excited helium (He*) to calibrate the interferometer. In a typical molecular beam system, the He* would exit a nozzle at a speed of 2.0×10^3 m/s [47]. This terminal velocity would be reached with a backing pressure behind the nozzle of 10 atm of He. Modern pulsed molecular beam systems [48, 49] reduce the volume of gas entering the vacuum chamber. This reduces collisional loss in the beam and requires less pumping of the vacuum system. These systems also allow for reducing the backing pressure necessary to form the jet and can be used to produce a lower speed. By varying the nozzle temperature and backing pressure pulsed beams of atomic hydrogen have been produced with 10^{16} atoms per sec with speeds as low as 1.2×10^3 m/s [50]. This is in the appropriate range for calibrating the interferometer. We will detect the He* with a position-sensitive MCP which will also serve as an active antihydrogen annihilator.

4 Current Status

4.1 Prototype Interferometer

We have a nearly finished prototype atomic interferometer that we could use to demonstrate the gravity measurement with a matter beam. This includes an operational metastable hydrogen beam that relies on quenching the 2S state with an electric field and detecting the resulting Lyman-α photon using a solar-blind photomultiplier tube. We would like to replace this detection system with a position-sensitive microchannel plate (MCP) to increase the count rate, to give us the ability to use a metastable helium (He*) beam, and to give us the ability to see fringes when the interferometer is misaligned. The metastable hydrogen beam is fairly weak and significantly faster than the antihydrogen beam will be, and both of these problems could be corrected by using a pulsed supersonic metastable helium beam. The MCP could also be used with soft x-rays to align the interferometer. The position sensitive MCP system would cost up to \$25k. In addition to this, we estimate that making this prototype operational would require \$21.2k for new equipment, \$31k in operational funds, as well as 12 person-weeks of technician time from Fermilab and a URA Visiting Scholar position (or equivalent).

The prototype interferometer uses 1.5-cm diameter gold gratings with a 0.9921-micron period. These are spares from the Chandra X-ray telescope's low-energy spectrometer, and were donated by the Max Planck Institute for Extraterrestrial Physics. The gratings are supported on plates which will be mounted inside a 10" stainless-steel pipe, which in turn will be supported inside a vacuum chamber. The mounting plates have piezo-electric actuators to adjust their position, and their position relative to the other plates is monitored by a RASNIK system [51] and a pair of optical interferometers.

With the addition of an MCP as mentioned above, when the interferometer is misaligned, we could observe a Moiré fringe pattern in the MCP that will indicate how to move the gratings to get them aligned. The MCP would also allow us to correct for imperfections in the gratings. We would like to use an MCP in the antihydrogen interferometer as an active annihilator.

4.2 External Funding

We have submitted a proposal to the National Science Foundation to fund construction of the equipment needed to capture antiprotons, make antihydrogen, and measure the gravitational force on the antihydrogen with an atomic interferometer. The proposal asks for $3.6M to support nine of the institutions in the collaboration over the next three years. We expect a decision on this proposal soon, and should Fermilab decide they are interested in our experiment, it would be most helpful for this information to be conveyed to the NSF as it might positively influence the decision on this funding.

Hbar Technologies, LLC is negotiating with a private foundation to fund the construction of a low-energy antiproton facility at Fermilab. This facility would include an antiproton deceleration ring with stochastic cooling that would permit nearly all of the antiprotons to be trapped. Because the funding would be available immediately and because the building site is outside the accelerator's radiation field, construction could begin very soon. It should be possible to be ready to receive antiprotons in calendar 2009. The deceleration ring design is based upon an existing accelerator at Indiana University Cyclotron Facility and would be funded in the third year. There is a possibility of using surplus magnets instead of building magnets, in which case the deceleration ring could be complete as soon as summer 2010. Many of the early milestones of Hbar Technologies' business plan coincide with the needs of AGE, so there are many opportunities for cooperation that will speed up the availability of low-energy antiprotons.

The Raizen group has funding to develop the trapping and cooling methods for hydrogen, antihydrogen, deuterium, and tritium. This includes a small grant for exploratory research for one year from NSF ($100k) and a pending regular NSF proposal ($703,066 for three years). In addition, they have a two-year grant from the State of Texas for $120,000 to support this same research.

5 Other Related Efforts

As emphasized in [1], the search for suppressed "non-Newtonian" components of the gravitational force has been an ongoing area of interest despite the difficulty of the experiments. (A review of some of the difficulties encountered may be found in [52].) A number of pioneering searches have nonetheless been carried out over many years. The key measurement using antihydrogen has only recently become feasible and is now proposed at CERN as well as at Fermilab. The high antiproton production rate of the Fermilab Antiproton Source offers significant advantages at Fermilab vis à vis the CERN AD.

The modern phase of this field can be said to have started with the work of Witteborn and Fairbank [53]. Although, due to Fairbank's death in 1989, their plan to make gravitational measurements with positrons did not come to fruition, they did set a limit on anomalous gravitational interactons of electrons. Such measurements using charged (anti)particles are bedeviled by many subtleties of residual electromagnetic interactions [52]. Despite this, a proposal to measure the gravitational force on a beam of antiprotons was pursued for several years [54], although it ultimately did not lead to a measurement.

A limit on the possible difference between the gravitational interactions of neutrinos and antineutrinos was derived by LoSecco from observations of neutrinos from SN1987a [55]. Nieto and Goldman [1] observe that this observation does not constrain possible deviations from Newtonian gravity on distance scales very much smaller than the size of our galaxy; it also does not necessarily constrain the gravitational interactions of (anti)baryonic matter. (There is also some unavoidable uncertainty whether in fact both neutrino and antineutrino events were detected [56], a condition necessary to draw any conclusions about antimatter gravity.)

The idea to measure the gravitational acceleration of neutral antimatter (and thereby dramatically reduce the confounding effects of stray electrical and magnetic fields) has been receiving increasing attention [7, 8, 57–62], as well as considerable recent impetus from the success in forming antihydrogen in traps at the CERN AD. Compared to the ongoing effort to search for CPT violation by precisely comparing the atomic spectrum of antihydrogen with that of hydrogen, it does not necessarily require the production and trapping of ground-state antihydrogen (a challenging goal that still has not been attained).

Prior to the present proposal, the most recent efforts (both focused on the CERN AD) are that of the AEGIS Collaboration [61] and a competing one [62] involving members of the ASACUSA Collaboration. The AEGIS Collaboration propose a 1% measurement of the gravitational acceleration of antihydrogen atoms using a classical Moiré deflectometer. They propose a more elaborate scheme than ours, where antihydrogen is to be formed at rest in a Rydberg state in a Malmberg–Penning trap using a charge-exchange reaction with positronium. The desired states of positronium and antihydrogen are to be produced and cooled with the aid of various laser manipulations. They will then accelerate the Rydberg antihydrogen atoms towards the deflectometer via their atomic dipole moments using a gradient electric field (Stark acceleration). The competing Letter of Intent [62] is also under consideration at CERN [63]. It discusses an approach that promises better systematics but lower statistics than that of AEGIS, and projects a 5-year effort culminating in the gravity measurement. The LoI is focused on methods to form $\overline{\mathrm{H}}$ at very low energy by making use of $\overline{\mathrm{H}}^+$ ions. The gravity measurement is described in [60] and involves cooling the antihydrogen to the $100\,\mu$K range, dropping it, and measuring the time of flight. The authors expect that this method can determine $\bar{g}$ with a precision better than 0.1%.

5.1 Comparison with the Present Proposal

The stacking rate for antiprotons at Fermilab typically exceeds 20×10^{10} per hour, so more than 4×10^{12} antiprotons are available per day. Presently all these are used for the Tevatron program, but a small percentage of these could be decelerated and used for antihydrogen production with minimal impact on the Tevatron's integrated luminosity. Even before the deceleration ring is built, with a mere five hours' antiproton production, using a degrader and a reverse linac we could trap in excess of 10^8 antiprotons. As noted in Section 3.4, the CERN experiments are able to convert in excess of 10% of their antiprotons into antihydrogen, but we would only need to convert 1% of these 10^8 antiprotons into an antihydrogen beam in order to make the 0.6% measurement shown in Figure 4. By contrast, the AEGIS Collaboration discusses producing ~ 100 to 1000 antihydrogen atoms over the course of some hundreds of seconds. To accomplish this they anticipate accumulating antiprotons in the trap over many AD cycles. As they emphasize, to measure each antihydrogen atom in the AEGIS deflectometer one by one and then combine these for a 1% measurement will require careful attention to alignment stability, monitoring, and calibration over periods of several weeks. (Although it may well be feasible, all in all this does appear something of a technical tour de force, which perhaps provides another rationale for the ASACUSA-inspired LoI [62].)

After the Tevatron program ends, or when the deceleration ring is operational, we will be able to trap far more antiprotons. We expect to reach systematics-limited measurements with the transmission-grating interferometer in the range of 10^{-4} to 10^{-6}. On the other hand, the Raman interferometer should only need a few thousand trapped antihydrogen to reach a precision of 10^{-6}, but this measurement may remain statistics limited even when the deceleration ring is operational. The systematics limits for measurements of local g with matter are at the level of 10^{-10} [64].

6 Impact on Tevatron and NuMI

It should be noted that, should AGE be ready for antiprotons before the Tevatron program ends, the initial operation of this experiment would be compatible with Tevatron operations. The impact on both Tevatron luminosity and NuMI integrated flux will be minimal in the operating mode we propose, as only a single bunch per day of antiprotons need be decelerated for this effort, probably at the end of a Tevatron shot. Of course, we would be able to make good use of additional shots on those rare occasions when antiprotons were not needed for the Tevatron, as we expect the measurement to be limited by statistics.

7 Summary

A key pillar of our understanding of the universe, General Relativity, has never been directly tested with antimatter. The opportunity to do so lies within our grasp. The results will be of great interest regardless of the outcome. Even the generally expected result will represent a unique and important measurement, and the high-precision phase might tell us about new forces not yet seen elsewhere. Because most of the needed components already exist, the measurement can be done relatively quickly and inexpensively. This high-profile project will garner enormous positive attention among the general public. It is just and fitting that such an initiative occur at Fermilab, the world's leading antiproton facility. We must act now before the initiative is seized elsewhere.

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Letter of Intent: Antimatter Gravity Experiment at Fermilab

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Abstract

Fermilab's unique ability to accumulate large numbers of antiprotons makes it possible to directly measure the gravitational force on antimatter for the first time. Such a measurement will be a fundamental test of gravity in a new regime, directly testing both the equivalence principle and the prediction of General Relativity that matter and antimatter behave identically in the gravitational field of the earth. We propose to decelerate antiprotons in the Main Injector and transfer them into an antihydrogen-production Penning trap. The antihydrogen will emerge from the trap in a low-velocity beam and pass through an atomic interferometer where the gravitational deflection will be measured. A 1% measurement should be possible soon after antihydrogen production is established. A possible follow-on phase of the experiment (beyond the scope of this LoI) can use laser-based interferometry techniques to measure much more precisely any difference between the gravitational forces on matter and antimatter and search sensitively for a possible "fifth force" significantly weaker than gravity.

[1]Also at Muons, Inc.

Contents

1 Motivation

Most physicists expect the gravitational acceleration of antimatter to be no different from that of matter, but this belief has not been directly verified by experiment. The theory of General Relativity (GR) is based upon the equivalence principle, which states that the force of gravity on any object is independent of the object's composition. This principle has been verified to high precision with matter, and GR has strong experimental support. Proposed quantum theories of gravity generally include additional terms that can violate the equivalence principle and/or the inverse-square dependence on distance [1]. The direct measurement of the acceleration of antimatter in the Earth's gravitational field is a way to test a fundamental assumption of GR in a new way. Even if the result turns out to be consistent with the predictions of GR it would extend the equivalence principle and be a classic test of that theory, and a possible follow-on, high-precision measurement will be sensitive to possible new forces much weaker than gravity.

To date, experiments have not even ruled out the possibility that antimatter in the gravitational field of the earth will rise rather than fall.[2] Physicists have on occasion argued that K^0 mixing already implies stringent limits on possible differences between the gravitational interactions of matter with matter and of matter with antimatter [2].[3] But it has also been argued that the observed CP violation in the K^0 system may in fact be a consequence of gravitational repulsion between quarks and antiquarks [3, 4]. In the end, the best way to determine the gravitational force on antimatter is a direct

[2] As remote as this possibility may seem, it has been considered in the literature, including speculation that it could provide an alternative explanation for the observed cosmic baryon asymmetry [5]; even a possible role in dark energy has been suggested [4].

[3] See Sec. 4 for discussion of other relevant limits.

measurement. We are proposing to make this measurement at Fermilab in the near future for a modest cost.

2 Method

The gravitational force on antimatter can be measured by directing a low-velocity beam of antihydrogen through an atomic interferometer and measuring the gravitational phase shift [6,7]. The atomic interferometer can transmit a large fraction of the beam, and the amount by which the interference pattern shifts as the beam traverses the interferometer measures the gravitational deflection of the beam, so it is possible to efficiently measure deflections on the scale of the interference pattern. Details of antihydrogen production and the interferometer are discussed below.

2.1 Low-Energy Antimatter

Antiprotons from Fermilab's antiproton source can be decelerated in the Main Injector and transferred to a new experimental enclosure at MI-9. Such operation has been previously discussed by Jackson [8], and some planning and partial construction for it has already occurred. Plans for the enclosure are shown in Figure 1. Deceleration of protons in the Main Injector has already been demonstrated to 3 GeV/c [9]. Demonstrating that the Main Injector magnets can ramp down to 2 GeV/c was accomplished during the same studies, and an advancement in RF technology developed by Hbar Technologies, LLC now makes deceleration of antiprotons down to 1 GeV/c possible with existing FNAL infrastructure. Studies of deceleration ramps can be done without beam in the Main Injector, and six 4-hour study periods with a proton beam are sufficient to determine whether 1 GeV/c (or lower) is achievable.

A carrier pipe, shown in Figure 2, was already installed for a low-energy transfer line to bring the antiprotons to the new experimental enclosure to be built at MI-9. Here the antiprotons can either be decelerated further in a small ring, or at the cost of some inefficiency, simply run through a degrader to reduce their energy to the point where they can be caught in a Penning trap. Design studies have been performed to estimate the yield of trapped antiprotons using degrader parameters given in Table 1 (see Figure 3). While the design may not be fully optimized, preliminary results indicate an efficiency of $\approx 5 \times 10^{-4}$. Once in a Penning trap, antiprotons are easily cooled to cryogenic temperatures by electrons in the trap. The electrons cool by synchrotron radiation to the temperature of the trap walls, and the antiprotons are cooled by collisions with the electrons [10].

NASA is currently packaging up their High Performance Antiproton Trap (HiPAT) and related equipment, shown in Figures 4 and 5, for shipping to HBar Technologies. This trap will be used for the gravity measurement. The existing HiPAT cryostat is already configured to meet the needs of the experiment. The H^- and proton sources and associated optics are also already configured to commission the experiment. Some

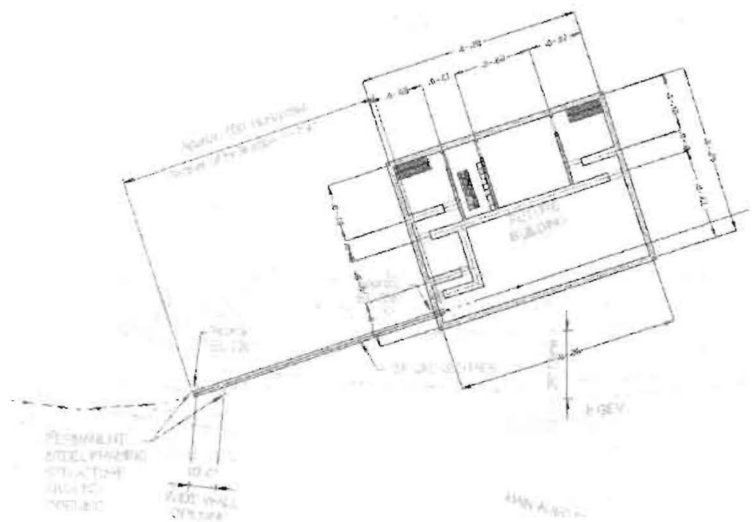

Figure 1: Design for an experimental enclosure to be built at MI-9 to house experiments using low-energy and trapped antiprotons.

modification to the existing electrode structure is needed for the initial commissioning of the experiment, and we anticipate that a new electrode structure optimized for low-velocity antihydrogen formation will be built. The new structure will be housed in a vacuum pipe with ends that mate to gate valves and include non-intercepting vacuum connections that allow antiproton injection from one end and antihydrogen emission from the other end.

To make antihydrogen, positrons are needed in addition to antiprotons. Positrons with the needed parameters can be accumulated from a ^{22}Na source using apparatus that is now commercially available [11]. This source, shown in Figure 6, can provide 8×10^6 positrons/sec from a 50 mCi ^{22}Na source. The positrons are accumulated in a trap using a differentially pumped spoiled vacuum [12]. The ATHENA collaboration has used this technique to achieve positron densities of $2.6 \times 10^{10}/\text{cm}^3$ [13].

2.2 Antihydrogen Production

Two groups at CERN have been making antihydrogen at the CERN Antiproton Decelerator (AD) since 2002 [14, 15]. The primary goal of these groups has been to trap antihydrogen in order to perform spectroscopy for high-precision *CPT* tests, so they are attempting to produce antihydrogen with extremely low velocity. Antihydrogen is produced by trapping cold antiprotons and positrons in separate potential wells in a Penning trap and causing the antiprotons to overlap with the positron plasma.

The velocity distribution of the antihydrogen produced by the ATRAP collaboration is shown in Figure 7. The antihydrogen is made in a beam along the axis of the trap

Figure 2: End of carrier pipe where it penetrates the wall of the Main Injector tunnel. This pipe was installed to enclose a low-energy beamline from the Main Injector at MI-10 to the experimental hall at MI-9. The four penetrations on the ceiling also lead to the location of the future MI-9 enclosure.

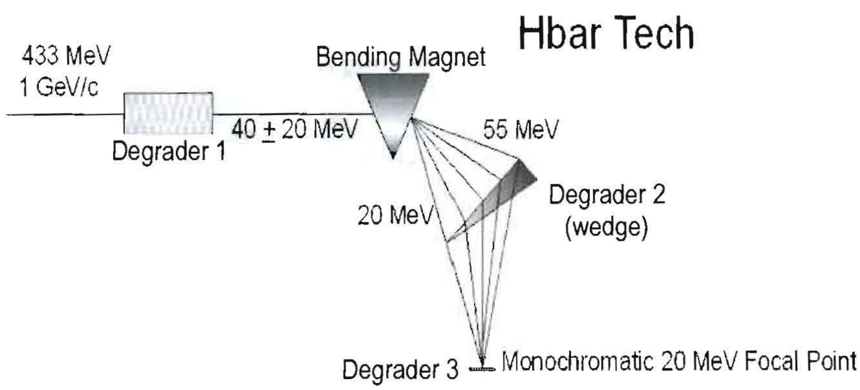

Figure 3: Degrader design studied by Hbar Technologies, LLC.

Table 1: Degrader configuration studied.

Intial $\bar{p}$ momentum:		1 GeV/c
Degrader 1:	geometry	cylindrical
	material	Fe
	thickness	16.75 cm
	$\bar{p}$ survival	50%
Degrader 2:	geometry	magnetic wedge
	$\bar{p}$ survival	~100%
Degrader 3:	geometry	foil
	material	Al
	thickness	25 μm
	$\bar{p}$ survival	50%
Trap injection efficiency:		0.2%
Overall efficiency:		5×10^{-4}

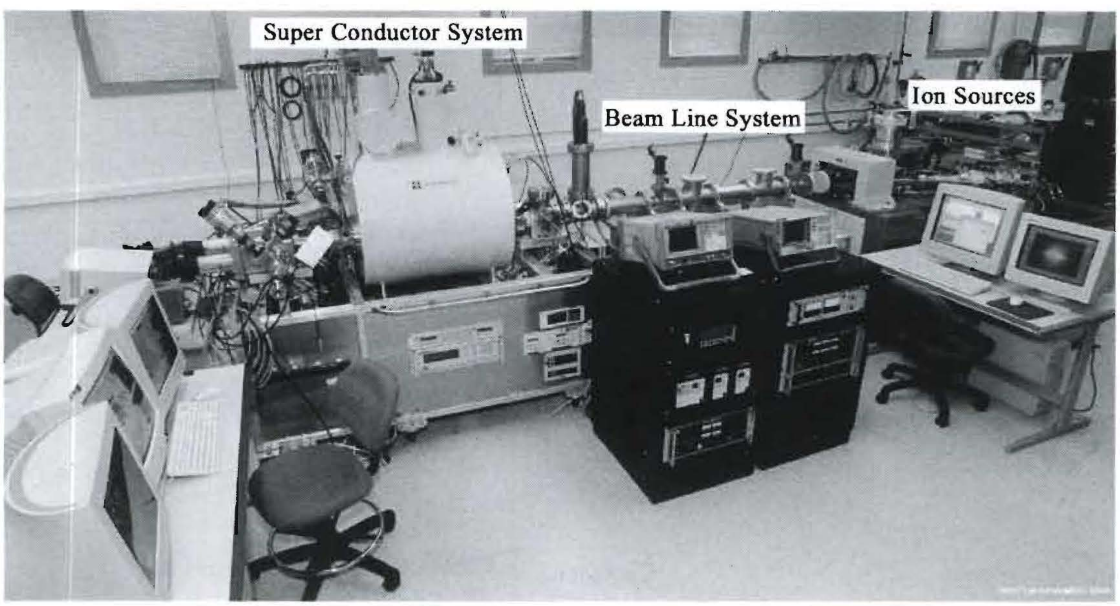

Figure 4: NASA's High Performance Antiproton Trap (HiPAT), which will be used for the Antimatter Gravity Experiment.

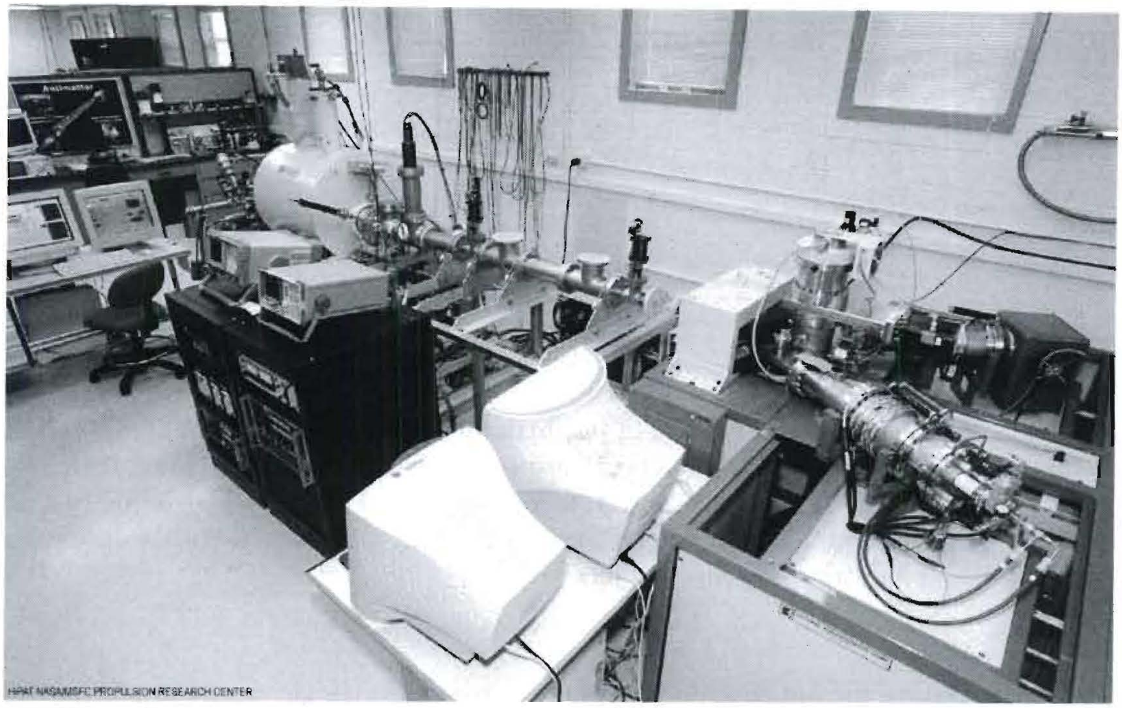

Figure 5: Ion sources for HiPAT.

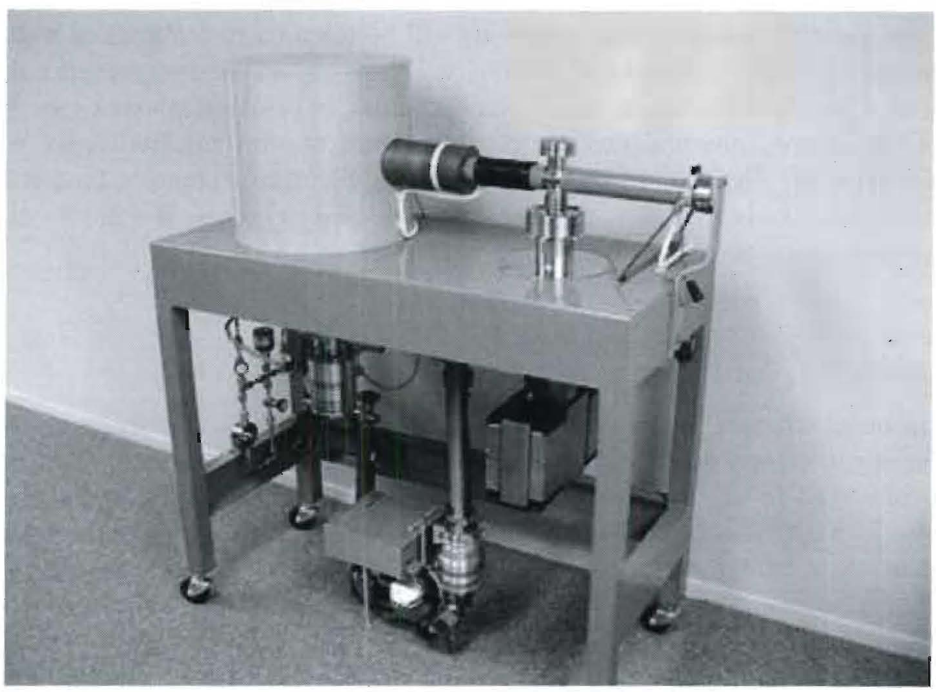

Figure 6: A commercially available positron source [11].

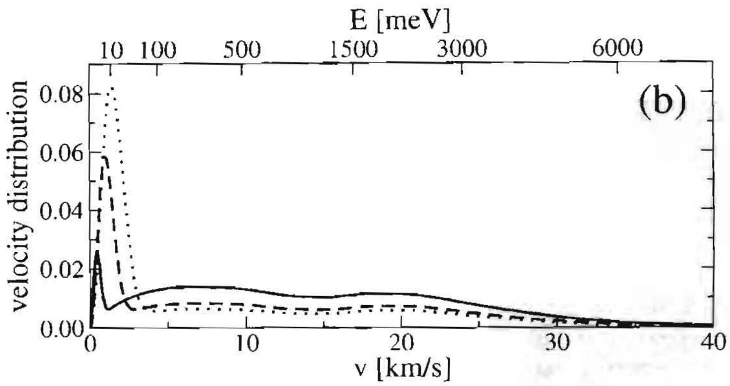

Figure 7: The velocity distribution of antihydrogen produced by the ATRAP collaboration. The three curves are for average antiproton velocities corresponding to $K_B T_{\bar{p}} =$ 1 meV (solid), 2 meV (dashed), and 5 meV (dotted). The long, high-velocity tail is believed to come from antihydrogen atoms that charge-exchange with hot antiprotons in side wells of the trap. (From reference [16].)

by gently heating the antiprotons so that they pass through the positron plasma. The low-velocity peak corresponds to the energy given the antiprotons, while the long, high-velocity tail is believed to come from charge exchange of these low-velocity antihydrogen atoms with hot antiprotons in side wells of the trap [16].

For the gravity measurement, positrons will be trapped in a potential well separate from the antiprotons, and the antiprotons will be accelerated by a small voltage to a velocity of a few km/sec before they pass through the positron plasma (see Figure 8). Some of the antiprotons will pick up positrons and become antihydrogen, which will exit the trap in the direction of the antiproton's momentum. The rate for antihydrogen production in a strong magnetic field by the three-body reaction $\overline{p} + 2e^+ \to \overline{\mathrm{H}} + e^+$ has been calculated [17] to be

$$\Gamma = 6 \times 10^{-13} \left(\frac{4.2}{T}\right)^{9/2} n_e^2 \; [\mathrm{s}^{-1}] \tag{1}$$

per antiproton, where T is the absolute temperature and n_e is the positron density per cm^3. For a sufficiently high positron density, a significant fraction of the antiprotons will be converted to antihydrogen every time they pass through the positron plasma. For example, with conservative values of $n_e > 10^7/\mathrm{cm}^3$ at a temperature of 4.2 K, each antiproton has a >0.6% chance of becoming an antihydrogen when passing through a 10-cm-long positron plasma at 1 km/s. This may be an underestimate; for example, this calculation neglects radiative combination and the three-body reaction $2\overline{p} + e^+ \to \overline{\mathrm{H}} + \overline{p}$, which should enhance the antihydrogen production rate for the high antiproton densities achievable at Fermilab. However, we show below that there is a substantial margin for the measurement even if the production rate is substantially below this

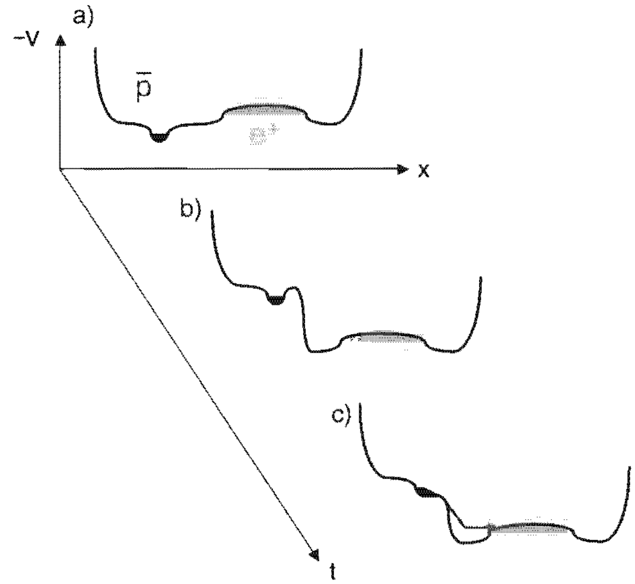

Figure 8: Cartoon of a) trap potential vs x at $t = 0$ showing antiprotons (red) and positrons (green) in separate wells (note that due to their opposite charges they are portrayed as sitting "above" and "under" their wells, respectively); b) and c) are snapshots showing voltage manipulations to accelerate the antiprotons such that they pass through the positrons: at time b), the $\bar{p}$ well potential is "raised" (made more negative) in preparation for $\bar{p}$ acceleration; at time c), the potential barrier between the $\bar{p}$ and e^+ wells is dropped and the $\bar{p}$'s are accelerated through the e^+ well.

estimate.

Since the gravitational deflection measured by the interferometer is a function of velocity, either the $\overline{\rm H}$ beam needs to have a narrow, well-defined velocity distribution, or the velocity of individual antihydrogen atoms needs to be measured. By accelerating the antiprotons through the positron plasma with a known voltage at a specified time, not only will the velocity be known to within the thermal velocity spread of the antihydrogen, but we can also measure the velocity by recording the time of flight.

Antiprotons that do not make antihydrogen will remain in the trap and be recycled. There are a number of ways of handling this. For example, voltages can be applied that keep the antiprotons synchronized as they oscillate back and forth through the positrons. In any case it is likely that half of the antihydrogen atoms would be produced going in the wrong direction, but it should be possible to recapture most of these by field ionizing the antihydrogen that goes in the wrong direction.

Because most of the antiprotons that are not converted into antihydrogen on a single pass through the positron plasma can be recycled, the efficiency for making antihydrogen on a single pass is not a critical parameter. It will only affect the total number of cycles needed to convert the antiprotons to antihydrogen. The cycle time is likely to be of order 10 ms; using this assumption and a 0.6% probability for creating antihydrogen per antiproton per cycle, then the time needed to convert half the antiprotons into antihydrogen is just over a second. The time to convert half the antiprotons to antihydrogen is still under two hours for a conversion probability of one in a million. To minimize impact on integrated Tevatron luminosity, and because a small fraction of the Antiproton Source production rate suffices for the proposed measurement, transfers of antiprotons are expected to be infrequent. Thus there is plenty of margin for the additional cycles that would be required should the antiproton-to-antihydrogen conversion probability turn out to be lower than estimated here.

As noted above, the high antiproton densities achievable at Fermilab will allow for an antihydrogen production mechanism that, to our knowledge, has not been considered for antihydrogen production at CERN. At the AD, it is expected that a dominant antihydrogen production mechanism is the three-body reaction $\overline{p}+2e^+ \to \overline{\mathrm{H}}+e^+$, which leaves most of the antihydrogen in a (highly excited) Rydberg state [18]. However, with a sufficiently high antiproton density the three-body reaction $2\overline{p} + e^+ \to \overline{\mathrm{H}} + \overline{p}$ should become important, and this charge-exchange reaction leaves the antihydrogen more tightly bound [16]. The charge-exchange reaction has been serendipitously observed at CERN with hot antiprotons in side wells [16]. We propose to take advantage of this reaction by tailoring the release of antiprotons such that faster antiprotons would overtake slower antiprotons as they pass through the positron plasma. At this time we do not have a calculated rate for this reaction, but we expect it to be substantial because of the large fraction of antihydrogen that experienced charge exchange in the ATRAP experiment [16].

The antihydrogen production mechanism has been studied by the ATHENA Collaboration [19]. While the observed temperature dependence does not match the expectation for the three-body reaction $\overline{p} + 2e^+ \to \overline{\mathrm{H}} + e^+$, the rate is at least an order of magnitude higher than expected from radiative combination. So while the mechanisms for making antihydrogen are still not completely understood, it is clear that it is possible to make antihydrogen at a significant rate and with a velocity distribution appropriate for the gravity measurement.

2.3 Measuring $\bar{g}$ with an Interferometer

The most obvious method to measure $\bar{g}$ using the antihydrogen beam would be to collimate the beam horizontally and measure its position after it had propagated a sufficient distance in a drift tube. However, this method makes inefficient use of the antihydrogen. A more efficient measurement can be made using an interferometer. The concept is to set up an interference pattern with a pair of diffraction gratings, and to measure the phase of the interference pattern with a third grating. The phase shift caused by gravitation can be measured by comparing the phase shifts for beams of different velocities. The axis of the interferometer can also be rotated with respect to the direction of gravity; when the grating lines are vertical gravity will not affect the interference pattern. Calibrations with matter beams are possible as well.

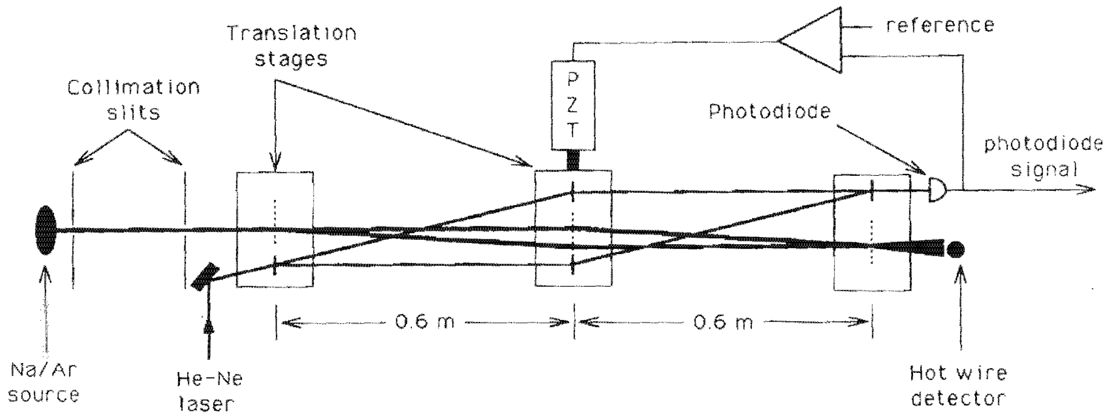

Figure 9: Schematic of the sodium-atom interferometer in use at MIT. A similar interferometer can be used with antihydrogen to measure the gravitational force on antimatter. Separated beams are not needed for the gravity measurement, so the collimator is unnecessary and the period of the diffraction gratings can be much larger. (From reference [20].)

Perhaps the ideal interferometer for this experiment is a configuration that has been used for both neutron and atom interferometry [20,21] (Figure 9). This interferometer consists of three equally spaced transmission gratings, each with identical line spacing. The first two gratings set up an interference pattern that is independent of both wavelength and the spatial coherence (incident wave direction) of the source [22]. This interference pattern has a spatial period equal to the line spacing of the gratings, so the phase of the interference pattern can be analyzed by using a third identical grating as a mask and measuring the transmission as a function of the mask's position. The interference pattern is localized in x (the direction perpendicular to the grating planes), so while the distance between the first and second gratings is arbitrary, the distance from the second to the third grating must match the distance between the first and second gratings. A diagram illustrating the principle of the interferometer is shown in Figure 10 and an example interference pattern is shown in Figure 11.

Not all of the diffraction orders from the first two gratings will contribute to the interference pattern. However, by using gratings with roughly 50% transmission (i.e., the slit width is half of the grating period), the even diffraction orders are suppressed, and most of the transmitted beam appears in the 0^{th} and $\pm 1^{st}$ orders in roughly equal amounts. The orders that will interfere are shown in Figure 10. Ideally, approximately 4/9 of the beam transmitted through the second grating (four of the nine principle diffraction orders) will contribute to the interference pattern.

The phase of the interference pattern can be measured by moving the third grating in the $\hat{y}$ direction. The transmission is then recorded as a function of the phase of the grating: the transmission is highest when the interference peaks fall on the slits.

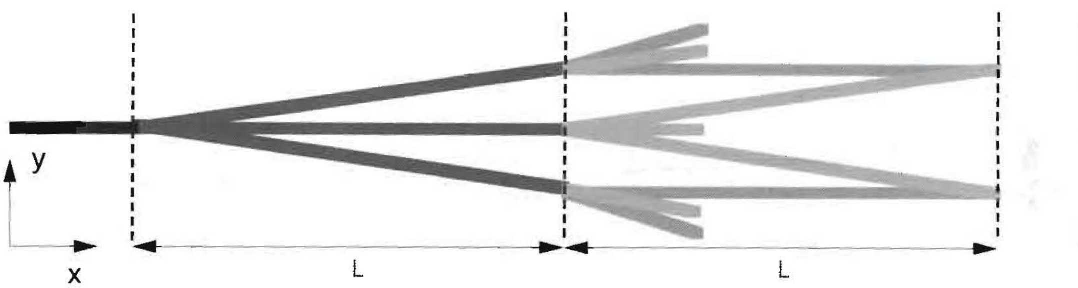

Figure 10: Principle of three-grating interferometer for measuring $\bar{g}$. The three diffraction orders shown will contain most of the transmitted beam in roughly equal amounts. The orders that are drawn to the third grating cause an interference pattern with a frequency that matches the grating's line spacing. The diffraction orders that are not followed to the third grating do not contribute to this pattern, but rather cause a flat background.

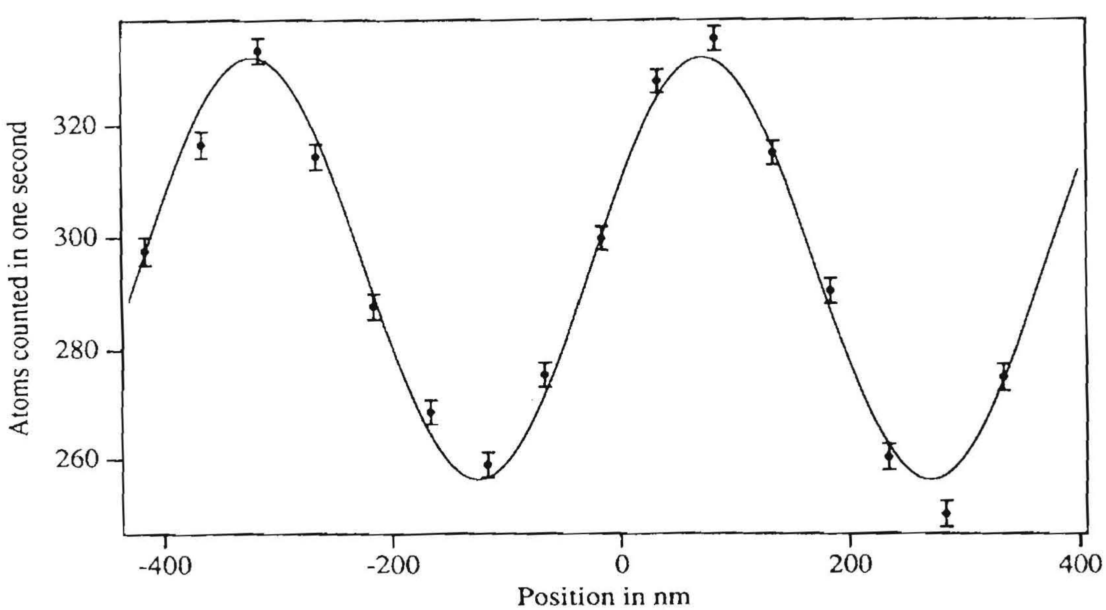

Figure 11: Interference pattern measured using sodium atoms in the MIT interferometer from 400 seconds of data; note suppressed zero. (From reference [20].)

The interference pattern shifts by the same amount that transmitted atoms are deflected while transversing the interferometer. Thus, for deflection D given by

$$D = \bar{g}\frac{L^2}{v^2}\,, \tag{2}$$

where L is the separation between successive gratings and v is the velocity of the antihydrogen, the resulting phase shift $\Delta\phi$ is

$$\Delta\phi = 2\pi D/d\,, \tag{3}$$

where d is the line spacing of the grating. It is important to note that while the interference pattern is independent of velocity (wavelength), the deflection (or equivalently the phase shift) due to gravity is not. This means that a large velocity dispersion can wash out the interference pattern when the phase shift due to gravity becomes significant, so the beam used to make this measurement must either have a sufficiently small velocity dispersion, or else the velocity of each antihydrogen atom must be measured.

We can illustrate this method for measuring the force of gravity using the parameters for a prototype interferometer that is under construction for this project by T. Phillips, working with a beam of metastable hydrogen atoms (rather than the currently unavailable antihydrogen). (The metastable beam provides a clean signature relative to background hydrogen in the apparatus.) This interferometer has gratings with $d = 1\,\mu$m and $L = 62$ cm. A beam of hydrogen traveling at 3 km/s would experience a gravitational deflection of $0.4\,\mu$m which corresponds to a phase shift of 0.8π rad for the interference pattern. The limiting uncertainties in calculating g from this measurement are likely to come from uncertainty in the velocity of the hydrogen atoms and uncertainty in the grating position. If we assume the hydrogen atoms are excited to the metastable state over a 1 cm region and the distance to the detector is 250 cm, then the uncertainty in the velocity measurement will be 0.4%. In order to match this uncertainty, the phase shift would need to be measured to 5 mrad. Reducing the beam velocity to 1 km/s would increase the deflection to $3.8\,\mu$m (7.5π rad) and the phase shift would need to be known to 48 mrad.

By using the interferometer used with sodium atoms [20] as an example, we estimate that we should be able to make a 1% measurement of $\bar{g}$ with a few $\times\, 10^5$ antihydrogen atoms incident upon the first grating of the interferometer. If the order of magnitude of the antihydrogen production rate calculated above is correct, then we should be able to produce many more antihydrogen atoms than this, and the measurement would not be limited by statistics. We expect the leading systematic uncertainty to be how well the dimensions of the interferometer can be controlled and measured.

The antihydrogen velocity distribution shown in Figure 7 would work for the gravity measurement, where the low-velocity peak would experience significant gravitational deflection while the high-velocity tail can be used to monitor the alignment of the interferometer.

The efficiency for the antihydrogen to contribute to the interference pattern will depend upon a number of design parameters, and this can be illustrated by working through an example. Each grating will have 50% open area, less whatever support structure is needed to keep the grating lines in place. If we take the support structure to be 5% of the area, the net beam transmitted through the first two gratings will be about 23% and on average about 11% will be transmitted through the third grating (the mask). Only four of the nine dominant diffraction orders will contribute to the interference pattern (see Figure 10). Imperfections in the gratings and misalignments will reduce the contrast of the interference pattern so if we take this reduction to be roughly a factor of two then about 3% of the beam will contribute to the interference pattern. Transmitted antihydrogen atoms annihilate on a final screen located a suitable distance downstream of the third grating, with the annihilation products detected as discussed in the next section. (Note that if desired, we can improve the statistical significance of our signal by separately measuring annihilations that occur on the third grating, in addition to those that occur in the screen.)

A significant inefficiency can arise from the transverse thermal velocity of the antiprotons, which leads to a broadening of the beam. For example, for antiprotons at 4.2 K accelerated with 30 mV to a velocity of 2.4 km/s, the beam would have a half-width of 25 cm at a distance of 225 cm, a reasonable distance for the third grating. It is not practical to have gratings this large; the prototype gratings mentioned above are about 1 cm in diameter, so would accept only 0.03% of the beam. This can be approximately quadrupled by lowering the temperature of the antiprotons to 1 K, or it can be raised to 2.1% by using 4-inch gratings [23], in which case lowering the antiproton temperature to 1 K again approximately quadruples the efficiency to 8.6%. Of course, the cost of lowering the antiproton temperature will need to be considered along with other technical considerations in determining the optimal configuration. Another way to raise the efficiency for converting antiprotons into antihydrogen that traverses the interferometer is to collimate by field-ionizing antihydrogen that would miss the interferometer, and then return the stripped antiprotons to the production trap.

These considerations are summarized in Table 2, based on representative performance assumptions discussed above. While it is premature to give precise estimates, and some of the efficiencies in Table 2 may well increase as the design is refined, at the order-of-magnitude level this estimate indicates the great potential of such an experiment at Fermilab. (For example, it far exceeds the intensities available at the CERN Antiproton Decelerator.) To the extent possible, we intend to refine these estimates over the next several months, although we recognize that some of them may require tests with trapped $\bar{p}$'s to establish with confidence.

2.4 Antihydrogen Detection

Antihydrogen annihilation in matter produces large signals which are easily detected in scintillator, silicon detectors, and wire chambers. It is possible to conduct this experiment by simply counting the net transmission through the interferometer with scintillators, but additional information gathered with more sophisticated detectors can add statistical power and aid in controlling systematic uncertainties. If possible,

Table 2: Illustrative rate estimates for antihydrogen production and detection (assuming 4″ gratings, 4.2 K operation, and use of a field-ionizing collimator).

$\bar{p}$ pulses/day	1
$\bar{p}$'s/pulse	10^{10}
Trapping efficiency	5×10^{-4}
Trapped $\bar{p}$'s/pulse	5×10^{6}
$\overline{\mathrm{H}}$ formation efficiency	10%
$\overline{\mathrm{H}}$'s/pulse incident on 1st grating	5×10^{5}
Background (noninterfering) $\overline{\mathrm{H}}$'s/pulse	5×10^{4}
$\overline{\mathrm{H}}$'s in interference pattern/pulse	10^{4}

the antihydrogen detector should monitor annihilation rates at each grating and at the final screen, which are separated by a few meters. Because the velocity measurement is crucial to our experiment, time resolution well below 1 ms is a necessity. Spatial resolution in the direction transverse to the beam should be as fine as possible, so that (ideally) the interference fringe pattern on the third grating and the final screen can be seen in as much detail as possible to aid in aligning the interferometer.

While there are many options that could be considered, a simple, economical, and trouble-free way of achieving these goals is by using one of the recently decommissioned large drift chambers from either CLEO or BABAR. Besides being complete (all hardware components plus online and offline software) and high-precision systems, as well as tolerant of fairly high rates, these drift chambers are long enough that the whole setup can be monitored with a single device. These devices are also self-triggering, which means that there is no need for additional detectors.

The BABAR drift chamber is 276 cm in length. The relevant parameters of the CLEO-c drift chamber are summarized in Table 3 (the spatial resolutions are taken directly from the CLEO Caliper web pages). When operated in their original environment, these detectors provide a measurement of five quantities per track: three momentum components and two distances of closest approach to the origin.

In the Antimatter Gravity experiment, there is no equivalent of the "Beam" signal, which provides the t_0 to the whole CLEO or BABAR detector. The chamber data are fitted in such a way as to extract two angles, two distances and one time for each track. Annihilation events with two or more charged tracks can be used to reconstruct precisely the location of the annihilation vertex and its most probable time. This technique is used routinely in CLEO to measure the size and shape of the luminous region at the interaction point, and most notably to monitor the bunch length, a quantity of great interest to the machine operators.

Assuming that the chambers can be transported and restarted without damage to their components or large misalignments, one expects a similar performance as in CLEO or BABAR. On one hand, due to the absence of a magnetic field, one has

Table 3: Summary of CLEO-c Drift Chamber nominal parameters, as applicable to the Antimatter Gravity experiment.

Parameter	Unit	Value
Wire length	cm	73–237
Inner diameter	cm	35
σ_x	μm	40–50
σ_z	μm	200
σ_t	ns	<50

a better-known time-to-distance relation in the drift cells, smaller overall correlation coefficients among the tracking parameters, and lesser multiple scattering between interaction point and tracker. On the other hand, without an inner detector, overall spatial resolution will be degraded by perhaps a factor of two.

From Table 3 one can see that the estimated timing resolution is excellent (below 50 ns) and probably exceeds the precision with which one knows the time of production of the antihydrogen. By reconstructing annihilation vertices on the third grating and on the final screen we will be able to observe characteristic interference fringes if the interferometer is rotationally misaligned. We will also be able to use the resolution along the beam direction (called σ_z in Table 3) to reconstruct the position of the gratings.

The use of a tracking detector to observe antihydrogen annihilations will provide far more detailed information about the annihilations than scintillators would, but it will also add considerable complexity to the experiment. We have not yet sought permission to use either of these drift chambers, and we will need to carefully weigh the benefits against the additional costs before determining the best way to detect antihydrogen annihilations.

3 High Precision Measurement

Should the initial measurement prove unable to distinguish the gravitational force on antimatter from that on matter, it would be desirable to make a precision measurement of the difference between the gravitational forces on matter and antimatter. This would be sensitive, for example, to a weak fifth force that coupled to baryon number. Atomic interferometers have been used to measure the gravitational force on matter to a part in 10^{10} [24]. This is done by launching atoms in an atomic fountain and using a laser pulse to split the atoms into a superposition of momentum states. These states separate in space, and a second laser pulse brings the states back together where they are recombined with a third laser pulse, but with a phase shift that depends upon local g (see Figure 12).

This technique can be used with hydrogen and antihydrogen to make a precision

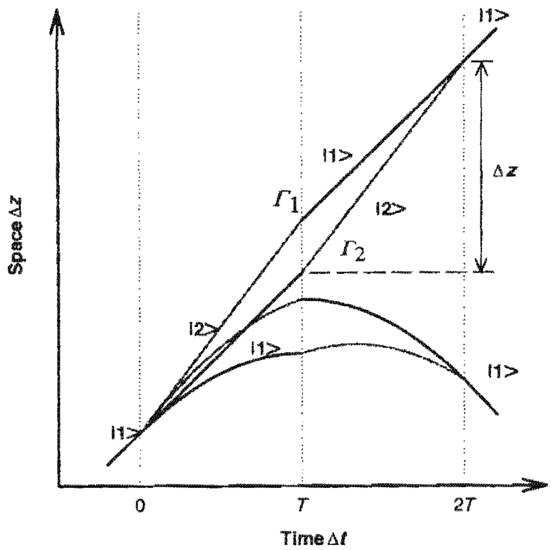

Figure 12: Phase space diagrams, in the presence and absence of gravity, for atom interferometer based upon $\frac{1}{2}\pi - \pi - \frac{1}{2}\pi$ pulse sequence. The first laser pulse splits the atoms into superpositions of two momentum states which separate spatially. The second pulse brings these split states back together, and the third pulse recombines them with a phase shift that depends upon local g. (From reference [24].)

difference measurement of the force of gravity on matter and antimatter [25,26]. However, unlike the initial measurement of $\bar{g}$, this will require a long program to develop the technology needed to trap and cool the neutral antihydrogen atoms.

4 Other Related Efforts

As emphasized in [1], the search for suppressed "non-Newtonian" components of the gravitational force has been an ongoing area of interest despite the difficulty of the experiments. (A review of some of the difficulties encountered may be found in [27].) A number of pioneering searches have nonetheless been carried out over many years. The key measurement using antihydrogen has only recently become feasible and is now proposed at CERN as well as at Fermilab. As we will argue, features of the Fermilab Antiproton Source and its recently developed mode of operation ("stashing" of antiprotons in the Recycler) offer significant advantages at Fermilab vis à vis the CERN AD.

The modern phase of this field can be said to have started with the work of Witteborn and Fairbank [28]. Although, due to Fairbank's death in 1989, their plan to make gravitational measurements with positrons did not come to fruition, they did set a limit on anomalous gravitational interactons of electrons. Such measurements using charged (anti)particles are bedeviled by many subtleties of residual electromagnetic interactions [27]. Despite this, a proposal to measure the gravitational force on a beam of antiprotons was pursued for several years [29], although it ultimately did not lead to a measurement.

A limit on the possible difference between the gravitational interactions of neutrinos and antineutrinos was derived by LoSecco from observations of neutrinos from SN1987a [30]. Nieto and Goldman [1] observe that this observation does not constrain possible deviations from Newtonian gravity on distance scales very much smaller than the size of our galaxy; it also does not necessarily constrain the gravitational interactions of (anti)baryonic matter. (There is also some unavoidable uncertainty whether in fact both neutrino and antineutrino events were detected [31].)

The idea to measure the gravitational acceleration of neutral antimatter (and thereby evade the confounding effects of stray electrical and magnetic fields) has been receiving increasing attention [6, 7, 32–37], as well as considerable recent impetus from the success in forming antihydrogen in traps at the CERN AD. Compared to the ongoing effort to search for *CPT* violation by precisely comparing the atomic spectrum of antihydrogen with that of hydrogen, it does not require the production and trapping of ground-state antihydrogen (a challenging goal that still has not been attained).

Prior to the present proposal, the most recent (both focused on the CERN AD) are that of the AEGIS Collaboration [36] and a competing one [37] involving members of the ASACUSA Collaboration. The AEGIS Collaboration propose a 1% measurement of the gravitational acceleration of antihydrogen atoms using a classical Moiré deflectometer. They discuss a more elaborate scheme than ours, apparently to compensate for the much lower antiproton intensity at the AD. Antihydrogen is to be formed at rest in a Rydberg state in a Malmberg–Penning trap using a charge-exchange reaction with positronium. The desired states of positronium and antihydrogen are to be produced and cooled with the aid of various laser manipulations. They will then accelerate the Rydberg antihydrogen atoms towards the deflectometer via their atomic dipole moments using a gradient electric field (Stark acceleration). The competing Letter of Intent [37] is also under consideration at CERN [38]. It discusses an approach that promises better systematics but lower statistics than that of AEGIS, and projects a 5-year effort culminating in the gravity measurement. The LoI is focused on methods to form $\overline{\mathrm{H}}$ at very low energy by making use of $\overline{\mathrm{H}}^+$ ions. The gravity measurement is described in [35] and involves cooling the antihydrogen to the 100 μK range, dropping it, and measuring the time of flight. The authors expect that this method can determine $\bar{g}$ with a precision better than 0.1%.

4.1 Comparison with the Present Proposal

The feasibility of the present proposal stems from the recent implementation (for the Tevatron Collider) of antiproton "stashing" (with electron cooling) in the Recycler. As a result of this advance, the Recycler at most times during Tevatron operation contains of the order of 10^{12} antiprotons—a number which of course increases as antiproton accumulation progresses, until the stash is transferred to the Main Injector, accelerated to 120 GeV, and then transferred to the Tevatron for acceleration to 1 TeV and collisions with the counter-rotating 1 TeV proton beam. Apparatus is thus in place, and routinely functioning, that can transfer antiproton bunches from the Recycler to the Main Injector. Not only can the entire stash be transferred from the Recycler to the Main Injector, but it is also feasible to transfer individual bunches one at a time.

Once an antiproton bunch (of typically 10^{10} antiprotons) is transferred to the Main Injector, it can be quickly decelerated using techniques that were developed for this purpose by G. Jackson some years ago during a brief, dedicated study period [9]. The decelerated bunch can then be extracted "up" the Main Injector proton injection line. A needed switching magnet (to prevent the decelerated antiproton bunch from proceeding back into the Booster, and instead divert it to a new MI-9 transfer line to be built) has been designed for this purpose and assembled by Hbar Technologies, LLC [39]. Starting from this decelerated antiproton bunch, as discussed above, even a rather inefficient antihydrogen production mechanism should be capable of yielding of order 10^5 or so antihydrogen atoms (see Table 2), and we expect the rate to be substantially greater than this. By contrast, the AEGIS Collaboration discusses producing $\sim$ 100 to 1000 antihydrogen atoms over the course of some hundreds of seconds. To accomplish this they anticipate accumulating antiprotons in the trap over many AD cycles. As they emphasize, to measure each antihydrogen atom in the AEGIS deflectometer one by one and then combine these for a 1% measurement will require careful attention to alignment stability, monitoring, and calibration over periods of several weeks. (Although it may well be feasible, all in all this does appear something of a technical tour de force, which perhaps provides another rationale for the ASACUSA-inspired LoI [37].)

It should be noted that the impact on both Tevatron luminosity and NuMI integrated flux will be extremely minimal in the operating mode we propose, as only a single bunch of antiprotons need be decelerated, of order once per day, for this effort. The cost of the proposed effort is also anticipated to be small, with advantage taken of many existing resources, and only a handful of newly constructed items required.

5 Summary

A key pillar of our understanding of the universe, General Relativity, has never been directly tested with antimatter. The opportunity to do so lies within our grasp. The results will be of great interest regardless of the outcome. Even the generally expected result will represent a unique and important measurement; a high-precision follow-on phase might then tell us about new forces not yet seen elsewhere. Because most of the needed components already exist, the measurement can be done quickly and inexpensively. This high-profile project will garner enormous positive attention among the general public. It is just and fitting that such an initiative occur at Fermilab, the world's leading antiproton facility. We must act now before the initiative is seized elsewhere.

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