A CATCHING TRAP FOR ALL ANTIPROTON SEASONS

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ABSTRACT

We describe the origin, development, and status of the Los Alamos antiproton catching trap. Originally designed for the antiproton gravity experiment, it now is clear that this device can be a source of low-energy antiprotons for a wide range of physics, both on site, at CERN, and also off site.

Ach ihr Götter, große Götter
In dem weiten Himmel droben
Gebet Ihr uns auf der Erde
festen Sinn und guten Mut,...
– MENSCHENGEFÜHL, Goethe

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1 Introduction

One of the many characteristics we have come to look forward to in Herbert Walther’s work, is his taking of a known technique and, with exciting perception, his using it to produce wonderful new physics. A very spectacular example was Walther’s creation of ordered ion structures going around a “race track” [1]; that is, a radio-frequency, quadrupole, storage ring.

In honor of this spirit, we wish to describe the development of the Los Alamos, antiproton, catching trap, the uses of which may may go far beyond its original purpose. As reviewed in Section 2, the catching trap grew out of the need for some device which would slow down antiprotons extracted from the Low Energy Antiproton Ring (LEAR), at CERN. These low-energy antiprotons would then be used in an experiment to measure the gravitational acceleration of the antiproton. Ultimately, as detailed in Section 3, an elongated, cylindrical Penning trap was devised, modified, and completed for this purpose. As of today, approximately \(10^6\) antiprotons have been captured and cooled in it, after having been extracted from one slow spill from LEAR.

However, having accomplished this, it is now clear to a wide community that, serendipitously, this device is a made-to-order source of new particles: low-energy antiprotons. In Section 4 we discuss some of the many uses to which this device may be put. For example, they can be used in low-energy, antiproton, nuclear and atomic physics experiments, as a storage vessel for the creation of antihydrogen, and as a source to fill small portable traps. These traps could then be sent to universities and research institutions all over the world.

2 The History of the Trap

A decade ago, no direct test of gravity had ever been performed on antimatter. This, and the lack of unambiguous evidence for the “orthodox” view that antimatter experiences the same interaction as matter, led to the suggestion that an experiment be performed at LEAR to measure the gravitational acceleration of the antiproton [2].

The idea was to cool antiprotons, in some manner, down to approximately 4 K. Then the antiprotons would be released up a field-free “drift-tube,” similar in principle to the one Witteborn and Fairbank used to measure gravity on electrons [3]. After release, the hottest antiprotons would quickly go to the top of the drift tube, with the slower ones taking longer. The cutoff time of the distribution would be when the least energetic of the antiprotons would just have enough energy to overcome the gravitational potential. This cutoff time is given by

\[
\tau = \sqrt{\frac{2L}{g}},
\]  

(1)

where \(L\) is the field-free length of the drift tube. As an example, for normal gravity and a length of one meter, the cutoff time is 0.452 sec. Statistically, about \(10^6\) antiprotons must be sent up the drift tube to obtain a value of \(g\) for antiprotons relative to \(g\) for negative hydrogen ions to a few percent.
This part of an actual experiment remains no small feat, and continues to be developed [1, 2]. The force of gravity is equivalent to $10^{-7}$ V/m, which shows to what extent field variations, like from the patch effect [4], must be overcome. The antiprotons must also be launched in bunches, containing no more than approximately 100 particles, to prevent self-interactions from disturbing the measurement. Thus, the idea is to store $10^6$ antiprotons in a small launching trap within the drift tube, and launch them 100 at a time by slowly dropping the voltage trapping the antiprotons.

But a first problem for the experiment was to decelerate the slowest antiprotons from LEAR, with energies of approximately 5 MeV, to 4 K. The original idea [2] was to reverse the injection linac and use an electrostatic generator to slow down the particles. By the time an official proposal was made [3], the choice was to use a radio-frequency quadrupole accelerator (RFQ) as a “decelerator,” after which the particles entered a Penning trap where they would be resistively cooled, and eventually injected into the drift tube.

In the end, however, a number of factors led to the decision to use a very long Penning-style trap as the primary apparatus in which to store and cool the antiprotons from LEAR. These factors included the cost involved with an RFQ, the success of experiment PS196 [4] in trapping a smaller quantity of antiprotons in a small Penning trap by first using a simple foil as a degrader, and the results of direct foil experiments compared with TRIM model calculations [3].

The entire apparatus of the antiproton gravity experiment is schematically described in Figure 1. With luck it will help answer the exciting question of what is the gravitational acceleration of antimatter [7]. It may be interesting to note that now, nearly a decade after the original proposal was brought forward and after many arguments have been made that gravity on antimatter should not be any different from that on matter, it is becoming clear from the “dark matter problem” that we really do not understand gravity even in most of the normal universe, much less in the antimatter world [10].

### 3 The Trap Today

At CERN, antiprotons are produced at very high energies. Presently, the lowest energy at which they are delivered to physics users is 5.9 MeV, at the Low Energy Antiproton Ring (LEAR) [11]. To further reduce this energy a number of methods have been proposed and partially tested: Deceleration by an RFQ operated in reversed mode [12], slowing down antiprotons in a dilute gas in the “anti-cyclotron” [13], and degrading the antiproton energy by passing the beam through thin foils [12, 13]. The degrading foil method is by far the simplest and cheapest of these proposals. During the past few years it has been used by two experiments at LEAR with promising results [4, 16]. We therefore discuss this method in some detail.

When protons or antiprotons pass through matter they loose energy by collisions with the nuclei of the material. If the thickness of the material is increased, particles eventually are stopped in the material and, in the case of antiprotons, annihilate. Using a Monte Carlo computer code based on energy loss data for protons, one can calculate both the expected linear density of material at which a maximum number of particles with low energy is transmitted and also how large the number for a specified
energy bin should be. One finds this optimum thickness to be near the point where 50% of the incoming particles are transmitted. These calculations predict that as much as 5% of the incoming antiprotons from LEAR will be transferred into an energy bin between 0 to 50 keV \[15\].

At this energy it is possible to electro-magnetically capture the antiprotons in a Penning trap and to further reduce their temperature using electron cooling \[17\], stochastic cooling \[18\], or resistive cooling \[19\]. Such a capture has been successfully performed by experiment PS196 \[16\]. They obtained a capture efficiency of $2 \times 10^{-4}$ per keV well depth. More than 20,000 antiprotons were captured in a small Penning trap and cooled to temperatures below 100 meV. Observed cooling times were approximately 10 seconds. Energy widths as small as 9 meV were directly observed by releasing the trapped antiprotons from the trap.

After the antiprotons are cooled, the trap well can be lowered again to accept a new pulse of antiprotons into the same trap. This method of “stacking” has been demonstrated by the PS196 team and approximately 100,000 cold antiprotons have been captured into their Penning trap, utilizing about 10 consecutive pulses from LEAR.

### 3.1 Trapping of 30 keV antiprotons from LEAR

In order to determine the ultimate efficiency that can be achieved for degrading and capturing antiprotons in a Penning-trap, the first part of the PS200 experimental set-up was installed at LEAR \[4\]. This part consists of a Penning type trap of 50 cm total length and 3.8 cm diameter, situated in the horizontal, cryogenic bore of a superconducting magnet capable of producing a magnetic field of up to 6 Tesla. Figure 2 shows the general layout of the “test” experiment and the different detectors used to monitor the incoming beam and to verify the capture of antiprotons.

A particle pulse from LEAR is transported to the front end of the experiment. After exiting the LEAR beam line through a 12 micron titanium window, the pulse passes through a parallel-plate avalanche counter (PPAC) for beam monitoring. The beam then goes through a gas cell, for fine tuning of the energy degrading, and enters the vacuum system of the experiment through another 12 micron titanium window. By then the beam energy has been reduced to approximately 3.7 - 4.0 MeV. Due to the transverse scattering caused by the material the particles pass through, a relatively large angular spread is introduced into the beam. But the beam can be focused by the fringe magnetic field of the superconducting magnet. In particular, by choosing a specific magnetic field strength for the particular energy of the incoming beam, the focal point can be placed onto the entrance foil of the trap. In this 135 micron gold-coated aluminum foil the antiprotons loose more energy by collisions with the atoms of the foil material.

Assuming proper adjustment of the additional degrader material upstream, an optimum number of low energy particles will exit from the downstream face of the foil. These particles will be reflected by the electrical potential at the far end of the trap and travel back towards the entrance electrode. This electrode is then rapidly ramped up to potential before the particles can escape, thereby capturing them within the volume of the trap.
The principal design parameter for the trap is the length necessary to capture particles of energies up to 30 keV emerging from the entrance foil during a LEAR pulse of typically 200 ns duration. At a 1 m round-trip distance, the time remaining after the last particle has entered the trap before the first particle is reflected back to the entrance is 220 ns for a 30 kV well depth. Our current 30 kV pulser has a 125 ns rise, allowing a total of 95 ns for jitter and uncertainty in the trigger timing.

From these parameters we have constructed a trap structure which consists of 7 electrodes: the entrance foil, a central region comprised of five cylinders (2 endcaps, 2 compensation electrodes, and the central ring), and a cylindrical, high-voltage, exit electrode. The lengths and diameters have been carefully chosen to produce a harmonic, orthogonalized, quadrupole potential in the central region [20]. For the purpose of the initial antiproton capture, the trapping region is defined by the entrance foil and the high-voltage exit electrode. Except for the small central region, the trap has no harmonic properties and is the characteristic “catching trap” referred to throughout this paper.

The central, harmonic region serves a dual purpose: to initially hold cold electrons in preparation for the electron cooling, and then to collect the cooled antiprotons after the electron cooling has taken place. This part of the trap is instrumented with two independent tuned circuits to detect electrons and antiprotons via the signals induced in the compensation rings.

To establish the capture of low-energy antiprotons, they are released from the trap after a predetermined storage time. The release is accomplished by lowering the potential of the down-stream end-cap of the trap linearly with time, the time constant being large compared to the oscillation period of the particles in the trap. Particles will escape from the trap when their kinetic energy is greater than the potential barrier.

The annihilation of antiprotons on the surface of the microchannel plate detector (MCP) is detected by using scintillators outside the magnet dewar as well as by direct counts from the MCP. To reduce the background rate in the “hot” accelerator environment, the scintillators are used in a 2-fold coincidence set-up and can additionally be gated by the MCP pulses. The detection efficiency has been deduced from Monte Carlo calculations [4] to be approximately 7%, a value which has been experimentally confirmed using slow, continuous spills from LEAR.

This all generates a time-of-arrival spectrum which reflects the energy distribution of the particles in the trap prior to their release. Figure 3 shows such an energy spectrum of approximately 500,000 antiprotons released from the trap 500 msec after the pulser had fired to capture a pulse delivered from LEAR to our experiment.

To measure the storage time of antiprotons in our trap, the delay time between capture and release is varied. The number of detected antiprotons for each of these “shots” is normalized to the total intensity reading from the NE110 beam monitor. The results are plotted in Figure 4.

3.2 Cooling of antiprotons

During earlier storage time measurements a noticeable change in the spectral shape was noticed. After storage times of typically around 15 - 20 seconds, high-energy
particles could no longer be observed and the energy distribution had started to shift towards later channels in the release spectrum without a decrease in the total number of particles. After 30 - 40 seconds all counts in the arrival-time spectrum where concentrated at energies below 1 keV. Figure 5 shows a selection of energy spectra for 3 different storage times (8, 20, and 70 seconds). Such a cooling time would require an electron density of approximately $10^8$ electrons/cm$^3$ [17].

As later tests revealed, electrons were continuously produced by field emission from sharp points on the trap electrodes. These electrons were stored inside the well and cooled rapidly by synchrotron radiation. In some recent experiments we installed an electron source, consisting of a hot filament and appropriate extraction and focusing electrodes, in the fringe magnetic field region. Electrons produced by this source were trapped, cooled by synchrotron radiation, and collected in the central well.

Using both a resonant detection technique as well as extracting these electrons from the central well and counting them with the MCP, we established that we can load the inner well with $10^8$ electrons using a primary electron beam of 50 mA for 10 - 30 seconds. Antiprotons oscillating in the large catching trap interact via Coulomb interaction with these electrons and dissipate energy into the electron cloud. It, in turn, is continuously cooled by synchrotron radiation. Finally, both electron and antiproton clouds arrive at a thermal distribution in equilibrium with the ambient temperature of the apparatus.

One of the main problems is the small overlap between the antiprotons oscillating in the 50 cm long catching trap and the electron cloud confined to the central region of the harmonic well. Standard electron cooling calculations assume the two clouds to be completely overlapping. A first-order approximation consists of diluting the number of electrons, $10^8$, into the volume occupied by the antiprotons. Under these conditions, this effective electron density is only $2 \times 10^6$ e/cm$^3$. From this density we calculate an initial time constant for cooling of 140 seconds. This estimate is certainly only a lower limit, since it does not account for the actual dynamics of the interaction between the two clouds. The actual time constant could be higher by a factor of ten. Accordingly, in a recent experiment, where we carefully avoided any additional loading of electrons by corona discharges, no cooling was observed.

Another source of the observed cooling could be collisions with the residual gas. Assuming the main component of the residual gas to be helium, the fractional energy loss of an antiproton per collision is 0.33. Choosing a typical collision rate constant of $2 \times 10^{-9}$ cm$^3$/sec, we find that an observed cooling time constant of approximately 20 seconds would require a neutral density of $8 \times 10^2$ cm$^{-3}$, or a pressure of $3 \times 10^{-11}$ Torr. At the same time, such a residual gas pressure would result in an annihilation-limited storage time of 100 to 1000 seconds, in agreement with the observed storage times during our 1993 runs.

Since then we have not only improved our control over the high voltage, but have also installed an “in-vacuum ultra-high vacuum valve” to separate the cryogenic bore from the room temperature region of the vacuum system. With this closed-off system we expect the residual gas pressure to be significantly reduced. According to the above estimates, not having observed any significant cooling at a delay time of 2000 seconds indicates that the residual gas density was less than $7.5 \times 10^5$ cm$^{-3}$, corresponding to a pressure of less than $3 \times 10^{-13}$ Torr.
While both the above scenarios are possible, we do not have enough data to distinguish between them. This will be part of the R&D program for upcoming runs. One way to attack this question consists of deliberately spoiling the cryogenic vacuum by opening the “in-vacuum” valve after a set of data in the closed cryogenic configuration has been taken. In this way we will be able to separate out the electron-density issues from the residual-gas issues.

3.3 Ejection of antiprotons from the PS200 catching trap

For most of the physics experiments envisioned at this time, the antiprotons will need to be ejected from the trap once the initial cooling has taken place. For the gravity measurement proposed in PS200 all antiprotons will be transferred in a single bunch into a small Penning trap at the bottom of the vertical time-of-flight experiment. Here they will be resistively cooled to 4.2 K and then released in bunches containing approximately 100 antiprotons each.

While a fast transfer of a single pulse is required for the gravity experiment, other experiments with ultra-low energy antiprotons will require a ‘semi’-continuous beam, possibly with timing information on the release of individual antiprotons. A number of possible schemes can be conceived of to extract the cloud of antiprotons from the PS200 catching trap in this way.

Note that one can not just lower the potential at one end cap over an extended period of time. Since all antiprotons will have been cooled to an extremely low temperature, one would only obtain an extraction during the very last fraction of the spill time. Instead, one can eject the antiprotons by an evaporative process. Here the axial or cyclotron resonance frequency of the stored antiprotons is weakly excited, leading to a continuous heating and a slow “boil-off” of particles from the well. The rate of boil-off can be controlled by the amplitude of the radio-frequency applied as well as by the detuning between the applied frequency and the resonant frequency. Test experiments conducted at Los Alamos using a smaller Penning trap filled with protons have generated continuous spills of protons for approximately 30 minutes at a time [21].

The above evaporative, slow spill can be used for experiments where a low intensity of antiprotons and no timing information is needed. But if a time structure is required (e.g., for time-of-flight studies of the energy loss in materials) a different method is proposed. This method was originally developed to eject low-energy electrons from a Penning trap. The time-of-flight of the ejected electrons through an inhomogeneous magnetic field was then used to determine the electron magnetic moment [22].

The well depth was slowly reduced, allowing electrons to leave the trap whenever their kinetic energy exceeds the well depth. Superimposed on this linear ramp was a series of triangular spikes with a half width longer than the oscillation period of the particles in the harmonic well. During the time period of one of these pulses all electrons occupying the energy band covered by the pulse amplitude were allowed to escape, generating a micro bunch with a defined start time.

A derivative of this method was used in the proton test experiments at Los Alamos: A series of rectangular pulses, with a FWHM slightly larger than the oscillation period of the trapped particles and an amplitude of 1 - 2 Volts, was superimposed onto the
constant trapping voltage. Additionally, a weak RF drive was applied at the axial resonance (or the cyclotron resonance) to continuously heat the particle cloud. The amplitude of this drive was such that continuous boil-off was not quite taking place. A multi-channel analyzer with a 200 ns/channel time resolution was triggered with the leading edge of each of these pulses and a time spectrum for 1000 individual pulses was obtained. The result (See Figure 6) was a pulsed beam with a time width of 1.2 $\mu$sec and a repetition rate of 100 Hz with one particle per pulse, on average.

4 The Potential Uses of the Trap

4.1 Nuclear physics with ultra-low energy antiprotons

The availability of low-energy antiprotons with a well-defined energy has generated substantial interest amongst experimenters who have studied low-energy antiproton phenomena over the past few years. In this subsection we describe two specific examples and compare the methods currently used to alternative methods, which are based on our catching trap and have advantages.

The first group of experiments is a series of measurements on energy loss and straggling of antiprotons passing through matter [23, 24]. These experiments were performed by passing the lowest-energy beam available from LEAR (5.9 MeV) through a degrader material and then using a time-of-flight tag to select the particles with a specific energy.

This method has distinct disadvantages at lower energies. If the thickness of the degrader material is increased to reduce the beam energy below approximately 1 MeV, both the energy spread and the angular spread increase dramatically. The energy spread becomes equal to the mean energy at approximately 1 - 2 MeV and the number of particles available at a given energy decreases drastically below 1 MeV. Under these conditions one can no longer speak of a “beam of antiprotons.” Not only is the number of antiprotons available at the energy of interest diminishing rapidly, requiring more and more integrated beam time from the antiproton source to accumulate appropriate statistics, but also the background due to “unwanted” particles at higher energy quickly becomes overwhelming. These high-energy particles can annihilate in the experimental set-up, producing false counts, and can even saturate the detector system.

Here our catching trap could serve as a bunching system to compress the phase space occupied by the antiprotons and to remove the high-energy background from the measurements. By utilizing a 30 kV well depth and by cooling the particles to less than 1 eV, one could achieve an enhancement of more than $10^4$ in energy density. This would allow experiments to explore energy regimes far below the current limit of 10’s of keV and to accumulate much better statistics in the low-energy region.

Using the PS200 catching trap, a well-defined energy beam could be produced with a very small energy spread, allowing the direct measurement of low-energy processes. A number of such experiments have been proposed by the PS194 collaboration [27]. Once approved, they could be performed over the next few years with a much reduced impact on the LEAR operation.
A second group of experiments which would greatly benefit from very low-energy, narrow-energy width, antiproton beams are those requiring ultra-thin targets. One example is the study of the formation and delayed decay of hypernuclei when antiprotons are stopped in thin target foils. These processes were studied at LEAR by the PS177 collaboration [26]. A shadowing method was used to distinguish between prompt decays inside the target and delayed decays of hypernuclei which had escaped the target. The lifetime of heavy hypernuclei in the region of uranium was measured to be of the order of $10^{−10}$ seconds. To improve this method it would be desirable to use thinner targets, thus allowing a larger fraction of the formed hypernuclei to escape. To maintain a reasonable stopping rate in these ultra-thin targets a much lower energy of the antiprotons would be required.

These again could be obtained from our catching trap. By using the time structured extraction method described in the previous section one could generate short micro bunches of antiprotons at energies from a few hundred eV up to 30 kV. One would switch the potential of the long, cylindrical, high voltage exit electrode (or another electrode placed in the system for this specific purpose) during the time the bunch is shielded from external potentials while inside this electrode. The bunches would then be accelerated to the kinetic energy set by the potential applied to this electrode upon exiting. Model calculations indicate a near 100% efficiency for this process and experimental tests to characterize this beam structure are under way [21]. As an additional benefit the overall intensity of antiprotons entering the experimental set-up would be greatly reduced so the background from annihilations outside the target could be reduced almost to zero.

We currently are studying the possibility of measuring the structures of neutron and proton “halos” from prompt X-ray, Gamma-ray, and annihilation particle emission. Low-energy antiprotons entering a nucleus will preferably annihilate near the nuclear surface. The resulting pions have a high probability of missing the rest of the nucleus, thereby avoiding excessive excitation of the nucleus and subsequent fission of the target. The result is a “cold” daughter product with proton and neutron numbers of either (Z-1, N) or (Z, N-1), depending on whether the annihilation occurred on a neutron or proton. By detecting a distinct signature for the two possible routes the neutron distribution near the nuclear surface can be mapped out.

Jastrzebki et al. [27] presented the first measurements based on these ideas. But their experimental method is limited to cases where both daughters are radioactive, since off-line radio-chemistry methods are used for the reaction analysis. Our experiment would not be limited to radioactive annihilation products. Ultra-thin isotopically enriched targets and prompt measurements would be used to take advantage of the low energy properties of the extracted antiproton beam from the PS200 catching trap. Rather than studying the subsequent radioactive decay of the daughter products we plan to observe the (prompt) de-excitation of the daughters from the excited state to the ground state, *in situ*.

A first experiment will be using $^{48}$Ca. This isotope is interesting for two reasons. Firstly, it decays into radioactive products in both branches. Therefore, it can be used to calibrate our prompt experiment against the standard method. Secondly, theoretical model calculations exist [28] which predict a significant difference in the neutron/proton ratio at the nuclear surface between $^{48}$Ca and $^{40}$Ca, making this a choice of significant theoretical interest.
4.2 Antihydrogen production

The simplest system which can be studied by atomic physicists is the hydrogen atom [29]. It is the only one where theory can even attempt to find exact solutions, and the one which has subsequently been studied with great precision and success, both theoretically and experimentally. Naturally, it is a tantalizing dream that one might eventually be able to study its mirror image, the antihydrogen atom, with the same precision. Once could then either solidify or expand our understanding of fundamental symmetries. By stating this goal, we hence restrict ourselves to possibilities that would yield antihydrogen in an experimental environment suitable for precision measurements comparable to those achieved on the hydrogen atom. Since antihydrogen will always be an extremely rare object, one immediately realizes that it is a sensible approach to cool and trap the antihydrogen atoms.

A variety of schemes for producing antihydrogen has been proposed, and discussed in some detail [30]-[39]. The first mentioning of the possible production of antihydrogen in traps was by Dehmelt and co-workers [39]. For all practical purposes, the schemes we describe below are those which deserve close attention by the trap community.

4.2.1 Antihydrogen production using trapped plasmas

This method was originally proposed by Gabrielse’s group [34]. In a “nested trap” scheme, forming two Penning traps, the oppositely charged constituents (antiprotons and positrons) for antihydrogen production are held in separate clouds and cooled to 4 K, or even lower [40]. At a definite time, the two clouds are merged by lowering the electrostatic barrier between them, and antihydrogen is formed. The rate constant for this process is strongly temperature dependent and benefits vastly from cooling the particles. While the rate can be extremely high (with $10^7$/cm$^3$ positron density at 4.2 K one obtains $\Gamma = 6 \times 10^6$/s), one specific problem must be addressed. The antihydrogen atoms are formed in highly excited Rydberg states ($n \sim 100$). The atoms need to be quickly de-excited, before electrostatic field gradients from the Penning trap ionizes them. This de-excitation process needs to be carefully controlled since it also effects the capability of trapping the antihydrogen atom once it is formed.

4.2.2 Antihydrogen production by positronium-antiproton collisions

Alternatively, one can enhance the radiative antihydrogen formation rate by several orders of magnitude through coupling of the recombination process to a third particle. This increases the phase space constrained by energy and momentum conservation. Such a proposal has been made to create antihydrogen utilizing collisions between positronium atoms and antiprotons [37]. This process can be interpreted as Auger capture of the positron to the antiproton. The cross sections have been estimated by Humberston, et al. [36]. They used charge conjugation and time reversal to link the cross section for positronium formation in collisions between positrons and hydrogen to the antihydrogen formation cross sections.

Early calculations assumed both $\bar{H}$ and Ps to be in the ground state and obtained a broad maximum in the cross section of $3.2 \times 10^{-16}$ cm$^2$ at an antiproton kinetic
energy of approximately 2.5 KeV. Calculations of the total $\bar{H}$-formation cross section using classical and semi classical methods \cite{1} have obtained values of $\sigma(\bar{H})$ which are considerably larger than the ground-state results. Values for the formation of $\bar{H}$ in excited states are given by Ermolaev, et al. \cite{12} and indicate that there is a large cross section to low-lying excited $\bar{H}^*$ states, which therefore would be directly accessible to spectroscopic studies.

Charlton \cite{38} has discussed the formation of excited $\bar{H}^*$ atoms via collisions between antiprotons and excited positronium. The cross section follows a classical $(n_{Ps})^4$ scaling, where $n_{Ps}$ denotes the principal quantum number of the positronium atom, leading to large enhancements in the reaction rate. This process can also be utilized to preferentially populate specific low-level excited states for spectroscopic purposes.

4.3 Precision measurements using antihydrogen

Considering the effort necessary to produce antihydrogen one must ask what further physics benefits such an endeavor could yield. In principle, these can be found in two areas. A comparison of the results of spectroscopic measurements of hydrogen and antihydrogen would constitute a test of CPT at a level rivaling even the result on the kaon system. The study of the gravitational interaction of antimatter with the Earth’s gravitational field would test the validity of the weak equivalence principle (WEP) and possibly shed light on the problem of unifying gravity with the three other forces.

The precision of spectroscopic studies of hydrogen advanced enormously over the last decade. Today the highest precision has been achieved for the hyperfine structure ($6.4 \times 10^{-13}$) and for the 1s-2s level difference ($1.8 \times 10^{-11}$), from which one obtains the Rydberg. Based on the lifetime of the 2s state of 1/8 second and the natural linewidth connected to this, a precision of $10^{-18}$ for the measurement of the Rydberg has been speculated as being possible. This latter precision will most likely require using trapped hydrogen atoms, an environment which would be directly applicable to antihydrogen.

4.3.1 CPT invariance

Currently the best tests of CPT invariance have been performed in the kaon system followed by precision comparisons of the magnetic moments and masses of electron, positron, proton, and antiproton. The comparison of the inertial masses of the proton and the antiproton has now reached a precision of $1.4 \times 10^{-9}$ \cite{13}. In the strict sense this must be considered only a measurement of the ratio of the charge-to-mass ratios of the two particles. It has been proposed \cite{14} that by combining the direct determination of the cyclotron frequencies with the measurement of the Rydberg of protonium one could extract an independent CPT test. But with the current precision on the Rydberg \cite{15}, a CPT test of only $2 \times 10^{-5}$ is possible. Using the Rydberg of antihydrogen, one could construct a limit for the charge equality between antiproton and proton which is entirely based on frequency measurements, and could therefore yield a direct test of CPT at a level of $10^{-11}$.
4.3.2 Gravity on antimatter

Often the arguments are made that measuring gravity on charged antimatter is nearly impossible due to the interaction of the charge with stray electric fields and that it would be advantageous to use a neutral particle instead. To compare charged and uncharged experiments in a fair way one needs not only to consider the added complication of producing the antihydrogen atoms but also one must devise a possible method of measuring the gravitational acceleration with sufficient precision.

Although they are repeatedly discussed, purely ballistic methods to measure gravitational acceleration on antihydrogen atoms can be ruled out. Even if antihydrogen atoms could be laser cooled to the photon recoil limit of $T = \Gamma h/2k = 2.4 \text{ mK}$, this temperature would still correspond to a distribution of height of approximately $1 \text{ m}$ in the gravitational field. A precise determination of the centroid of a cloud of this dimension is not possible. Similarly, if one should be able to generate an atomic fountain with a mean energy of the photon recoil and a spread of half that value, the observed time-of-flight over a height of $10 \text{ cm}$ will be $(14\pm7) \text{ msec}$, again not yielding a precision measurement of $g$. The only hope in the latter case would be to perform an end point measurement similar to the PS200 proposal, but this time with more particles near the end point.

A potentially much more powerful method could be developed based on the work of Chu and collaborators [46]. In their experiment they used velocity-sensitive, stimulated Raman transitions to measure the gravitational acceleration, $g$, of laser-cooled sodium atoms in an atomic-fountain geometry.

In their method an ultra-cold beam from an atomic trap is launched upwards and is subjected to three subsequent pulses to drive a two-photon Raman transition between the $F = 1$ and $F = 2$ sublevels of the $3S_{1/2}$ state. A Raman transition is used to provide a large photon recoil velocity while still satisfying the metastability of the states necessary for long interaction times. A first ($\pi/2$) pulse prepares the sample in a superposition of the $|1, p\rangle$ and the $|2, p + \hbar k\rangle$ states. The second ($\pi$) pulse reverses the populations and a third ($\pi/2$) pulse causes the wave packets to interfere. The interference can be detected by probing the number of atoms in state $|2\rangle$. In the absence of any external forces acting on the atoms, the final state of an atom will depend on the phase of the driving Raman field.

This result can be extended to an atom falling freely in the gravitational field. In the frame of reference falling with the atom, the Raman light fields appear Doppler shifted linearly in time, which shows up as a phase shift varying as the square of the time:

$$\Delta \phi = -(k_1 - k_2)gT^2,$$

where $k$ is the wave number of the Raman light field and $g$ is the gravitational acceleration. Since the Doppler shifts ($\sim 2k_1gT$) are much larger than the Rabi frequency, an active frequency shift between the three subsequent pulses must be used to compensate for the deceleration of the atoms in the fountain.

Using a $50 \text{ ms}$ delay between the pulses, distinct interference fringes were observed and a least square fit to the data gave an uncertainty in the phase determination of $3 \times 10^{-3} \text{ cycles}$. This represented a sensitivity to $g$ of $\Delta g/g = 3 \times 10^{-8}$. A higher sensitivity is expected to be obtainable when cesium is used instead of sodium because
of a large reduction of the rms velocity spread. This current work was done with 30 K sodium atoms (representing a 30 cm/s velocity spread). For cesium one may expect an rms spread of only 2 cm/s. Therefore, a much larger portion of the sample will be contributing to the fringes.

A translation of this method to the hydrogen/antihydrogen case will not be trivial or straightforward. Hydrogen is (and antihydrogen certainly would be even more) ill suited for high precision measurements, notwithstanding the enormous advances in hydrogen spectroscopy over the last years [17]. A large problem will be imposed by the much higher photon recoil limit for laser cooling hydrogen atoms (~ 3 mK), which gives an rms velocity spread of approximately 700 cm/sec. A much faster fountain beam, resulting in greatly increased experimental dimensions, will have to be used. Therefore, a much larger fraction of the initial beam pulse will be lost due to ballistic spreading during the flight time of the sample and much less than 1% of the initial population can be expected to contribute to the fringes. This will also cause severe problems for the antihydrogen/hydrogen comparison, since the supply of antihydrogen atoms will be limited to small numbers and a re-trapping scheme needs to be incorporated into the experiment. Nevertheless, this method is the only one identifiable in the current literature which shows the potential of a high-precision measurement of $g$ on antihydrogen atoms.

4.4 Portable traps

A final application of the catching trap would be to develop smaller, portable traps into which antiprotons could be “decanted.” Such portable traps are actually prototyped by the launching trap of the antiproton gravity experiment. A current prototype is of approximate length 8 cm, and protons have been resistively cooled and stored in it for hours. A totally self-contained unit, with magnet and cryogenics, could be of height 1 m, diameter around 30 cm, with a total operational weight of approximately 100 kg.

With such a trap, one could envision a number of things. Firstly, every university could “bring the mountain to Mohammed.” For both small-scale research and education, each university could have its own supply of antiprotons. When the supply was gone, a new shipment could be obtained. There are also possible medical applications, such as producing short-lived medical isotopes, such as $O^{15}$, on site. Lastly, of course, it may be a better idea to bring the antiprotons for antihydrogen studies to outside laboratories, with their lasers and magnetic traps, rather than to try to bring this equipment to the hostile environment of an accelerator floor.

Ironically, in the end the biggest problem may be obtaining import licenses for antimatter.

5 Discussion

Recent advances in trapping and cooling of antiprotons have opened up new opportunities for research with ultra-low energy antiprotons. Already now significant improvements in testing CPT in the baryon sector have been accomplished, but the
ultimate precision will only be possible once antihydrogen can be formed and con-
tained. Long storage times of antiprotons and protons as well as recent advances in trapping and cooling of neutral hydrogen bring this once futuristic idea into the realm of the technically possible, even though experimentally challenging. A number of crucial steps still need to be taken. But in the meantime the possibility of a wide spectrum of interesting nuclear, atomic, and gravitational physics can be pursued.

Finally, having come full circle, we hope that the exciting physics that is now possible, with captured and cooled antiprotons, reflects well on the spirit that Herbert Walther has shown in his work. Most of all, we wish to join in on the admiring congratulations to Professor Walther on his 60th birthday.
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Figure Captions

Figure 1. A schematic diagram of the gravity experiment.

Figure 2. A diagram of the “catching trap” and the associated cryogenics, magnet, dewar, degraders, and detectors.

Figure 3. An energy spectrum of approximately 500,000 antiprotons released from the trap.

Figure 4. The number of antiprotons remaining in the trap as a function of time.

Figure 5. A selection of energy spectra for 3 different storage times (8, 20, and 70 seconds). This demonstrates cooling.

Figure 6. Time structure of a pulsed proton beam extracted from our Penning trap. The horizontal axis gives the time.
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