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THE PRODUCTION AND STUDY OF COLD ANTIPROTONS AND ANTIHYDROGEN

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A matter particle and its antimatter particle annihilate upon colliding. All of their respective masses turn quickly into energy. Antihydrogen atoms have been produced and suspended within a "container with no walls." Antihydrogen atoms, the simplest atoms made entirely of antimatter, were suspended and held in a Ioffe trap, at a magnetic field minimum. This proof-of-principle demonstration suggests that many more antimatter atoms could be confined in an improved Ioffe trap, and that these could be laser cooled as needed to use precise laser spectroscopy to study their properties with high precision.

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Production and Study of Cold $\overline{\mathrm{p}}$ and $\overline{\mathrm{H}}$

1 Overview and Statement of Objectives

AFOSR support launched and sustains this unique antimatter research study of antiprotons and antihydrogen, the annihilation of which produce the maximum possible energy per unit mass. This is the sole US-led research effort with low energy antiprotons. The practical goal is developing the unusual techniques required to produce and store atoms made entirely of antimatter, given that the slightest encounter with ordinary matter turns all their mass into energy as they annihilate.

The scientific objective, which gives this program a highly leveraged access to the world's unique and extremely limited supply of antiprotons, is to compare the properties of matter and antimatter particles and atoms to extremely high precision – providing the highest precision test of the fundamental CPT theorem with leptons and baryons. Specific scientific goals include

1. Comparing the magnetic moments of the antiproton and proton.
2. Comparing the charge-to-mass ratios of the antiproton and proton.
3. Using extremely precise laser spectroscopy to compare the structure of antihydrogen and hydrogen atoms.

Much progress has been made in pursuit of these goals, but significant challenges remain.

With regard to comparisons of the properties of the antiproton and proton, the original proposal to slow, cool and trap antiprotons with energies down to 4 K was made and realized as part of this research program. The antiproton and proton charge-to-mass ratios were then demonstrated to be equal in magnitude and opposite in sign to 9 parts in 10^{11} as part of this program, and to demonstrate that the gravitational force is the same for an antiproton and proton to 1 part in 10^6. During the most recent grant period, the first direct comparison of the magnetic moments of the antiproton and proton was carried out. One trapped antiproton was compared to one trapped proton to demonstrate that their magnetic moments were exactly opposite to 4 parts in 10^6. The comparison was 680 times higher in precision than achieved in previous comparisons. Steady progress is now being made in developing and introducing quantum methods that will eventually improve the comparison precision by up to an additional factor of 10^4, to make one of the most stringent test of CPT invariance with a baryon system. A second goal is to compare the antiproton and proton charge-to-mass ratios to higher precision.

All interesting comparisons of the properties of antihydrogen and hydrogen remain to be carried out. Using cold trapped antiprotons and positrons to make cold antihydrogen atoms, proposed as part of this research program, has been realized. Producing antihydrogen that is cold enough to be trapped in a neutral particle trap, proposed as part of this research program, was accomplished during the most recent grant period. In this very significant step forward, this research program realized 5 trapped antimatter atoms in their quantum ground state per trial. This is the largest number of trapped antimatter atoms realized in a trial but more atoms are needed. Immediate goals for the next grant period include greatly increasing the number of trapped antihydrogen atoms in their ground state. Another goal is demonstrating the first laser cooling of trapped antihydrogen, a major step towards antihydrogen spectroscopy. A combination quadruple-octupole Ioffe trap whose 600 amperes of current can be removed in tens of milliseconds, with a Ti vacuum enclosure just completed, is expected to allow these major steps forward, in combination with the methods developed during the most recent grant period to produce and control much larger plasmas of antiprotons and positrons.

A wide spectrum of physics subfields must contribute to these extremely challenging experiments, including atomic physics, plasma physics, nuclear physics, laser physics, non-linear and chaotic dynamics, etc. Continuous inventions of new methods and devices are required. One result is that the numerous students and postdocs trained in this program are well equipped to lead their own research efforts in national labs, in universities and in industry. This program produced solenoid designs that are available commercially for ICR, NMR and MRI imaging, and trap designs now being used in devices that analyze pharmaceuticals and chemical compounds. There are hundreds of scientific citations to the reports on this work that are published in leading scientific publications. Many of these results have been also reported in the scientific press, and in the more popular press. The American Institute of Physics chose the initial antihydrogen observations as the physics story of the year, and the recent antiproton magnetic moment measurement was widely celebrated. The PI presents many scientific colloquiums, popular scientific lectures and high school presentations based upon AFOSR-supported research each year.

The AFOSR support for this research program is highly leveraged. The supported work takes place at the only low energy storage ring in the world – a unique and substantial facility built at the world's leading particle physics laboratory (CERN). The storage ring facility is maintained, operated and supported by CERN and its personal. In fact, this substantial facility was specially built so that the antihydrogen research program proposed by the PI could be carried out, a vision made possible by the low energy antiproton techniques pioneered by this AFOSR supported research program.

2 Project Narrative

2.1 Motivations, Spinoffs and Broader Impacts

2.1.1 Tests of CPT Invariance

Whether reality is invariant under CPT transformations is fundamentally an experimental question. A primary motivation for this research program is to use precise laser spectroscopy to probe for tiny difference between antihydrogen ($\overline{\mathrm{H}}$) and hydrogen atoms, thereby providing the most sensitive tests of CPT invariance with baryons and leptons.

Experimental tests have made physicists abandon widely held but mistaken assumptions about fundamental symmetries – first that reality is invariant under P transformations and second that reality is invariant under CP transformations. The current assumption, that reality is invariant under CPT, is based in large part upon the success of quantum field theories (QFT) for which there is a CPT theorem if plausible assumptions (like causality, locality and Lorentz invariance) are made. Of course, this argument cannot be universal since gravity does not fit into a QFT.

String theory has no intrinsic CPT invariance except when taken to the limit of a quantum field theory. Theoretical investigations of possible CPT violations have thus been studied in the context of string theory [1, 2]. One widely used parametrization [3] considers standard model extensions that arise if Lorentz violations are not excluded, whether these originate in string theory or elsewhere. Quantitative comparisons of existing CPT tests and possible $\overline{\mathrm{H}}$ measurements [4] were provided.

A reasonable requirement for a CPT test with $\overline{\mathrm{H}}$ and H is that it eventually be more stringent than existing tests with leptons and baryons. Table 1 distinguishes the precision of the CPT test from the measurement precision since these can be very different. The most precise baryon CPT test is the 9×10^{-11} (90 ppt) comparison of the charge-to-mass ratios of the $\overline{\mathrm{p}}$ and p carried out as part of this research program [5]. For that measurement, as for proposed $\overline{\mathrm{H}}$ and H comparisons, the CPT test accuracy is the same as the measurement accuracy, so extremely precise measurements are required to probe CPT invariance at an interesting precision.

Table 1: Comparing the Precise CPT Tests for the Three Species of Particles

	CPT Test Accuracy	Measurement Accuracy	Enhancement Factor
Mesons (K_0K_0)	2×10^{-18}	2×10^{-3}	10^{15}
Leptons (e^+e^-)	2×10^{-12}	2×10^{-9}	10^{3}
Baryons ($p\bar{p}$)	9×10^{-11}	9×10^{-11}	1

The most accurate direct tests of CPT invariance are represented in Table 1 and Figs. 1-2. The CPT tests with leptons and mesons involve free enhancement factors that make the precision of the CPT test substantially greater than the measurement precision. The most precise lepton CPT test is a 2×10^{-9} comparison of measured magnetic moment anomalies of electron and positron [6], interpreted as a comparison of magnetic moments at 2×10^{-12}. A single meson CPT test is even more precise [7]. The delicately balanced nature of the unique kaon system makes it possible to interpret a measurement precision of only 2×10^{-3} as a comparison of the masses of the K_0 and $\bar{K}_0$ to an astounding 2×10^{-18}. One theoretical suggestion [1] is that quantum gravity could produce a CPT violation which is smaller by about a factor of 10.

2.1.2 Antihydrogen Spectroscopy Offers Higher Accuracy CPT Test with Leptons and Baryons

In principle, the comparisons of $\overline{\mathrm{H}}$ and H could make possible a CPT test at the meson precision. The 1s-2s transition has an extremely narrow fractional linewidth of only 5×10^{-16}. With a measurement signal-to-noise ratio of 200, line splitting by this factor would allow a comparison at the kaon precision. There are serious obstacles to attaining this extremely high precision, however, including a small number of available anti-atoms, a 2.4 mK laser cooling limit, a second-order Doppler shift, and possible Zeeman shifts depending on the configuration of the magnetic trap. Nonetheless, even a measurement at an accuracy of 10^{-13}, the level at which the difficulties mentioned may be manageable in the first traps [8], would give a substantially improved CPT test involving leptons and baryons.

The most precise laser spectroscopy of hydrogen attained so far [9] was obtained with a hydrogen beam by one group in this collaboration [10]. The narrowest observed width is still much wider than the natural

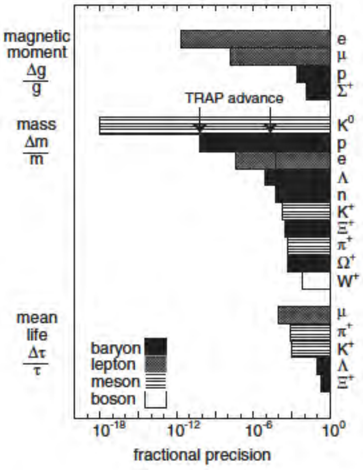


Figure 1: CPT Tests (primarily from the Particle Data Group compilation). Charge-to-mass ratio comparisons are included in "mass" measurements.

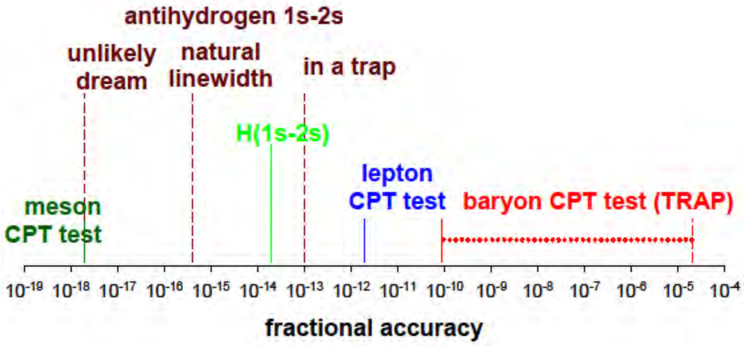


Figure 2: Relevant accuracies for the precise 1s - 2s spectroscopy of antihydrogen are compared to the most stringent tests of CPT invariance carried out with the three types of particles: mesons, leptons and baryons.

linewidth (Fig. 2) but we expect that steady and substantial improvements in accuracy will continue as they have been for many years. If such a narrow line were available for $\overline{\mathrm{H}}$ as well as H, the signal-to-noise ratio would be sufficient to allow the frequencies to be compared to at least 1 part in 10^{13}, a large increase in precision over the current tests involving baryons and leptons. The first use of cold trapped H for 1s-2s spectroscopy [11], in an environment similar in many respects to that we hope to arrange for $\overline{\mathrm{H}}$, comes very close to this linewidth, with substantial improvements expected if laser jitter had been reduced.

The ratio of the 1s-2s transition frequencies determine a ratio of Rydberg constants. In terms of other fundamental constants,

$$\frac{R_\infty(\bar{H})}{R_\infty(H)} = \frac{m[e^+]}{m[e^-]} \left(\frac{q[e^+]}{q[e^-]}\right)^2 \left(\frac{q[\bar{p}]}{q[p]}\right)^2 \frac{1 + m[e^+]/M[\bar{p}]}{1 + m[e^-]/M[p]}$$

(assuming the long range Coulomb interaction is the same for $\bar{H}$ and H). The only ratios on the right that have been measured accurately are the electron-to-proton mass ratio and the ratio of the electron and proton charges. This CPT test comparison thus clearly involves fundamental lepton and baryon constants but in a combination which makes it difficult to simply interpret the comparison as a measurement of the electron-to-positron mass ratio, or any other such simple ratio. The comparison of 1s-2s transition frequencies measured for $\overline{\mathrm{H}}$ and H would be a test of CPT invariance that involves the charges and masses of leptons and baryons at an unprecedented precision. Fig. 2 shows how the precision scales for $\overline{\mathrm{H}}$ 1s - 2s spectroscopy (mentioned above) compares favorably with that attained in existing CPT tests with leptons, mesons and baryons.

2.1.3 Gravitational Force on Antimatter

A second motivation for experiments which compare cold $\overline{\mathrm{H}}$ and H is the possibility to search for differences in the force of gravity upon antimatter and matter [12]. Making gravitational measurements with neutral $\overline{\mathrm{H}}$ certainly seems much more feasible than using charged $\overline{\mathrm{p}}$, for which the much stronger Coulomb force masks the weak gravitational force. Depending upon how cold is the antihydrogen we eventually achieve, it may be possible to measure the gravitational force on trapped $\overline{\mathrm{H}}$ [13], by adapting methods for measuring the free fall of cold atoms released from a trap [14], perhaps by ionizing H^- with a laser just above threshold, after first sympathetically cooling them to an extremely low temperature in an ion trap [15]. We are intrigued by the possibility of experimental comparisons of the force of gravity upon $\overline{\mathrm{H}}$ and H, and will pursue this direction when the techniques are sufficiently advanced to permit attaining an interesting level of precision. However, it will be challenging to reach the part per million precision we realized by comparing how the gravitation red shift [16] affected the rates of antimatter and matter clocks – the cyclotron frequencies of a single antiproton and a single proton in the same magnetic field [17].

2.1.4 Interesting Atomic, Plasma, Non-linear and Chaotic Dynamics, Atom Trapping, Particle and Atom Cooling, Etc.

Hundreds of citations to our $\overline{\mathrm{H}}$ papers give evidence that our path to $\overline{\mathrm{H}}$ spectroscopy and gravity studies takes us through many interesting and challenging physics problems of widespread interest.

2.1.5 Technological Spinoffs

Technology spinoffs arise insofar as technology must be pushed very hard if accurate $\overline{\mathrm{H}}$ spectroscopy is to be carried out. It is difficult to predict what results will be produced that will be useful to our culture, just like it was difficult to predict that pure science research would eventually lead to the transistor, the laser, the global positioning system, MRI imaging, etc. Since it is very difficult to predict such developments, we instead mention technological spinoffs from this program in the past.

1. A "self-shielding" superconducting solenoid system that cancels fluctuations in the ambient magnetic field was developed and patented at Harvard. Such systems are marketed for ICR mass spectroscopy, NMR, and MRI imaging systems.
2. A Penning trap that provides a large access to the trap interior, unlike the traditional hyperbolic electrodes used for precision experiments, allows even a single elementary particle to be isolated and detected. We first demonstrated such traps with antiprotons. Now chemists and physicists doing ICR spectroscopy (to analyze candidate pharmaceuticals, for example) utilize sample cells based upon these compensated trap designs.
3. We used cold trapped electrons to cool trapped antiprotons. The ICR community now uses such electron cooling to cool large trapped molecular ions, and the heavy ion community is investigating using positrons to cool highly charged ions.
4. The two photon spectroscopy techniques developed our collaborators at Gärching for hydrogen spectroscopy have revolutionized spectroscopy and laser frequency measurements. A continuous and coherent source of Lyman alpha radiation has also been developed just for these experiments [18, 19, 20, 21]. Optics and techniques for this portion of the electromagnetic spectrum are of great interest because of possible utility for producingand probing smaller structures.

2.1.6 Interdisciplinary Research: Particle Physics Goals and Atomic/Particle/Plasma/Laser Physics Methods

One challenge of this program is that it is not considered either mainline particle physics (despite its goals) or mainline AMO physics (despite its energy scale and methods). These days particle physicists are very focussed upon collider physics. Atomic physicists are very focussed upon realizations of model condensed matter systems, simple manipulations of quantum information, and the effect of fast or intense laser pulses. Even though CERN built a dedicated storage rings so that our $\overline{\mathrm{H}}$ physics aspirations could be pursued, no funds from any particle physics source in the US have ever been available for this work.

Enthusiasm for testing CPT invariance continues to grow, with whole conferences on testing CPT invariance being held in these days. There has always been interest in CPT within the subcommunity that studies the unexpected CP violation in the kaon system, but most particle physicists do not think much about testing the CPT theorem, and do not worry much about a new version of the earlier mistakes made by assuming first that reality was invariant under P, and then that reality was invariant under CP. When asked, the likely (and true) response is that there is a low expectation of finding a CPT violation. More is involved here than the herd instinct of those accustomed to working in collaborations with hundreds or thousands of collaborators searching for other possible violations of the standard model. Particle physicists are often not very familiar with the extremely precise low energy methods that must be employed. Often they do not realize how few are the experimental tests of our basic notion of CPT invariance, that current experimental tests with leptons and baryons are so much less accurate than the best test with mesons, and that a parametrization is available for placing limits on Lorentz and CPT violating extensions to the standard model.

Both the particle physics and AMO communities show interest in other ways, however. The PI gives large numbers of colloquia and invited talks each year, many of these in response to invitations from particle and atomic physicists – including the major particle physics centers at SLAC, Fermilab, DESY, CLEO, and CERN. $\overline{\mathrm{H}}$ studies have also be featured in community reports on opportunities in particle physics.

2.1.7 Popular Enthusiasm

The large number of citations and the large number of talks given by the PI illustrate the broad scientific interest in this $\overline{\mathrm{H}}$ research program. The great popular interest in antihydrogen is worth mentioning, as well, although it would be inappropriate for AFOSR to make a funding decision based in large part upon popular interest. Every significant step that we (and our competitors) make is widely reported in magazines ranging from “Physics Today”, ”Nature”, ”Science”, “Scientific American”, to “Discover”, to “Compressed Air”, etc. Such steps are also widely reported in newspapers ranging from the “New York Times”, to the “Washington Post”, to the “Christian Science Monitor”, to many local papers. The first observations of slow antihydrogen received such enormous publicity that the AIP selected this as the physics story of the year for 2002, and the high interest continues.

Tom Stoppard’s play “Hapgood” is based upon work done in this research program, as is Dan Brown’s best seller “Angels and Demons”. (What Dan Brown did for the Roman Catholic Church in the “Da Vinci Code”, he did for our antiproton research in “Angels and Demons”).

While it would be inappropriate for AFOSR to make a funding decision based upon overwhelming public interest in antimatter and anthydrogen, widespread public interest in quality science is good for science and is badly needed.

2.2 Results from the Most Recent Grant Period

2.2.1 Antiprotons Stored and Antihydrogen Produced Within Penning-Ioffe Fields

– Phys. Rev. Lett. 98, 113002 (2007)
– Phys. Rev. Lett. 100, 113001 (2008).

Many years before CERN built the AD for $\overline{\mathrm{H}}$ experiments, well before any of the $\overline{\mathrm{H}}$ collaborations had been formed, the PI proposed using cold $\overline{\mathrm{p}}$ to form $\overline{\mathrm{H}}$ cold enough to be trapped for precision spectroscopy [22]. A nested Penning trap was proposed to hold $\overline{\mathrm{p}}$ and e^+ so they would interact [23]. The $\overline{\mathrm{H}}$ that formed would then be caught in a superimposed Ioffe trap [22].

The first two ATRAP accomplishments of the current grant period were demonstrations that $\overline{\mathrm{H}}$ could be produced within the fields of a Penning-Ioffe trap [24, 25]. The demonstrations disproved claims by some in the competing ALPHA collaboration that it was “impossible” to form $\overline{\mathrm{H}}$ within the fields of a quadrupole Ioffe trap [26]. We first demonstrated that $\overline{\mathrm{p}}$ could be stored in a nested Penning trap long enough to form $\overline{\mathrm{H}}$ within a quadrupole Ioffe trap [24]. We next demonstrated that $\overline{\mathrm{H}}$ atoms can indeed be formed within the fields of a Penning-Ioffe trap [25]. Our 2008 report was followed by a similar report by ALPHA in 2010 ALPHA using an octupole Ioffe trap [27].

2.2.2 ATRAP and ALPHA Choose Different Paths

Our 2008 publication of the first $\overline{\mathrm{H}}$ production within a Penning-Ioffe trap also reported the first search for trapped antihydrogen atoms [25]. Given our detection efficiency, and no signals from trapped $\overline{\mathrm{H}}$ atoms, we set a limit that less than 20 $\overline{\mathrm{H}}$ atoms were being trapped per trial. No trapped $\overline{\mathrm{H}}$ atoms were also reported in 2010 when ALPHA reported its first $\overline{\mathrm{H}}$ production within a Penning-Ioffe field.

At this point the two collaborations chose different paths toward demonstrating trapped $\overline{\mathrm{H}}$ atoms in their ground state. We at ATRAP, convinced that 20 simultaneously trapped atoms was too few for $\overline{\mathrm{H}}$ laser cooling and spectroscopy, decided to first pursue producing more cold $\overline{\mathrm{H}}$ atoms from much larger and colder $\overline{\mathrm{p}}$ and e^+ plasmas. ALPHA instead used much smaller $\overline{\mathrm{p}}$ and positron plasmas, averaging over many trials, to look for smaller numbers of simultaneously trapped atoms.

Our choice resulted in a promising demonstration that 5 ± 1 ground state antihydrogen atoms could be simultaneously trapped for between 15 and 1000 seconds. However, since our approach required extra time to learn how to accumulate large $\overline{\mathrm{p}}$ plasmas and then how to form $\overline{\mathrm{H}}$ atoms from them, ALPHA received lots of publicity by reporting trapped $\overline{\mathrm{H}}$ atoms before we did. They reported a much smaller number of ground state $\overline{\mathrm{H}}$ atoms simultaneously trapped for comparable times (0.7 ± 0.5) [?]. None of the ALPHA reports or talks mention that producing and trapping cold $\overline{\mathrm{H}}$ was suggested [22] and popularized long ago as part of our AFOSR-supported research program, long before any collaboration members were involved in $\overline{\mathrm{p}}$ or $\overline{\mathrm{H}}$ physics. Averaging over many trials, ALPHA showed that less $\overline{\mathrm{H}}$ atoms were trapped when a somewhat resonant e^+ spin flip drive is applied [28]. We at ATRAP are not convinced that this approach could ever produce a resonance at an interesting level of precision and we did not pursue this direction.

ATRAP's larger number of simultaneously trapped $\overline{\mathrm{H}}$ vindicates our approach, but the number is still too small for useful measurements. So far the trapped $\overline{\mathrm{H}}$ number does not nearly increase in proportion to the number of $\overline{\mathrm{p}}$ in the $\overline{\mathrm{p}}$ plasma. We are confident that many more simultaneously $\overline{\mathrm{H}}$ atoms will be realized as we continue to learn how to better manipulate the large $\overline{\mathrm{p}}$ and e^+ plasmas.

2.2.3 Lowering the Trap Electrodes from 4 K to 1.2 K
– Nucl. Inst. and Meth. A 640, 232 (2011)

Our earlier $\overline{\mathrm{p}}$ trap electrodes had temperatures close to 4 K, lower than for all other $\overline{\mathrm{H}}$ experiments. In electron experiments at Harvard, the PI and his students demonstrated that the cyclotron motion of electrons enclosed within cold electrodes equilibrates with electrode temperature down to at least 1 K [29]. Accordingly, our pursuit of colder plasmas to make colder $\overline{\mathrm{H}}$ led us to lower our electrode temperature to 1.2 K [30].

This was challenging because the electrodes and enclosure are within a massive, 4.2 K Ioffe trap that is supported by a nearby 4.2 K helium dewar. Also, the electrodes and their vacuum enclosure are spread out over more than half a meter.

Fig. 3 represents the key elements of our solution [30]. Helium from a 4.2 K dewar goes through a capillary system to the 1 K pot reservoir which is pumped to make superfluid He. The superfluid cools the distant electrodes and their vacuum enclosure (not shown) to 1.2 K, leaving the massive Ioffe trap and helium dewar at 4.2 K. Thermal connections (not shown) cool the trap electrodes before the refrigeration system is cold enough to make superfluid helium. The system works very well.

Plasmas in equilibrium at 1.2 K electrode temperatures have not yet been realized, despite the Harvard demonstration that this is possible. Presumably this is because we have not yet been able to reduce radio frequency noise that heats plasma within the relatively open trap structure used for $\overline{\mathrm{H}}$ experiments so far. Our cold electrodes are necessary but not sufficient for realizing equilibrium plasma temperatures this low.

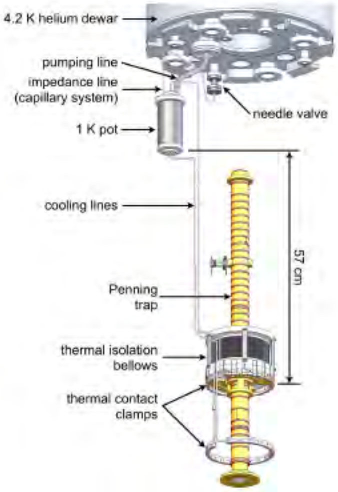


Figure 3: Essential components that cool the Penning trap electrodes to 1.2 K.

2.2.4 Much Larger Antiproton Plasmas
– Manuscript to be published

A considerable effort went into devising methods to efficiently cool large numbers of antiprotons. Fig. 4 illustrates that at ATRAP we can now accumulate ten million antiprotons for $\overline{\mathrm{H}}$ production. A detailed account of these methods has been prepared and should be published soon.

We continue to make progress in using larger numbers of trapped antiprotons to produce larger numbers of trapped $\overline{\mathrm{H}}$ atoms. There is every reason to expect that this progress will continue.

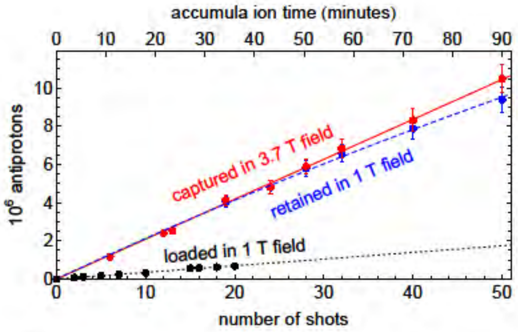


Figure 4: Accumulation of ten million $\overline{\mathrm{p}}$.

2.2.5 First Observation of Centrifugal Separation of Antiprotons and Electrons
– Phys. Rev. Lett. 105, 213002 (2010)

When $\overline{\mathrm{p}}$ and e^- plasmas rotate together within the same trap, the differing centrifugal forces should cause the heavier $\overline{\mathrm{p}}$ to migrate outside the e^- plasma [31]. For the first time, we were able to demonstrate centrifugally-separated $\overline{\mathrm{p}}$ and e^- plasma [32]. This indicates better control of the plasma temperatures, densities and radii than had been possible. Extremely good control and knowledge of the $\overline{\mathrm{p}}$ plasma parameters and geometry is critical for optimizing the production of trappable $\overline{\mathrm{H}}$. Our 2010 ATRAP report [32] was followed by the 2011 ALPHA report [33].

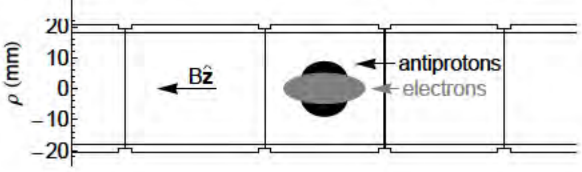


Figure 5: Trap and geometry of the centrifugally-separated antiproton and electron plasmas.

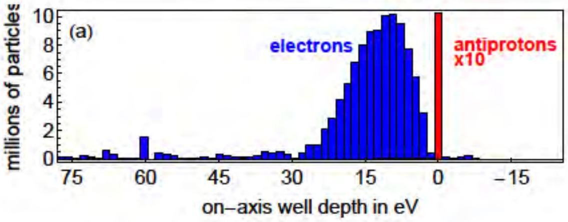


Figure 6: The centrifugal separation allows the electrons to leave the trap before the antiprotons.

2.2.6 First Observation of Embedded Electron Cooling
– Phys. Rev. Lett. 106, 073002 (2011)

We demonstrated electron-cooling of $\overline{\mathrm{p}}$ many years ago [34] for simultaneously confined e^- and $\overline{\mathrm{p}}$. The AD program to produce and study cold $\overline{\mathrm{H}}$ relies upon this method. Before now the number of e^- was much larger than the number of $\overline{\mathrm{p}}$ being cooled. For efficient $\overline{\mathrm{H}}$ production and cooling it is not desirable to have large numbers of e^- in the $\overline{\mathrm{p}}$ plasma. We thus devised a method to embed a small number of e^- within a much larger $\overline{\mathrm{p}}$ plasma, and to directly measure the resulting $\overline{\mathrm{p}}$ temperature. Fig. 7 illustrates how the temperature of the $\overline{\mathrm{p}}$ plasma is deduced from the slope of the number of $\overline{\mathrm{p}}$ that initially spill from their confining potential well as the well depth is reduced.

Fig. 8 shows that only 10^3 embedded e^- can heat (or cool) a plasma of 10^6 $\overline{\mathrm{p}}$. The 25 K equilibrium temperature observed is higher than should be possible – the 1.2 K temperature of our trap electrodes (p. 8 and [30]). (As mentioned, e^- experiments at Harvard e^- cooling to thermal equilibrium with the blackbody radiation from 1.2 K trap electrodes [29].) The $\overline{\mathrm{p}}$ plasmas with this low temperature would come from collisions with cold trapped e^- and e^+. Attaining lower equilibrium temperatures for e^-, e^+ and $\overline{\mathrm{p}}$ plasmas is an important goal for the next grant period.

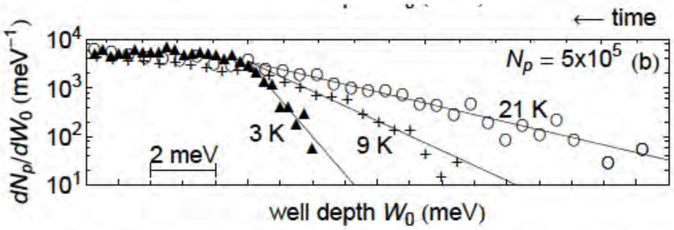


Figure 7: Deducing the $\overline{\mathrm{p}}$ plasma temperature from the slope of the number of $\overline{\mathrm{p}}$ that thermally escape a shallow trap.

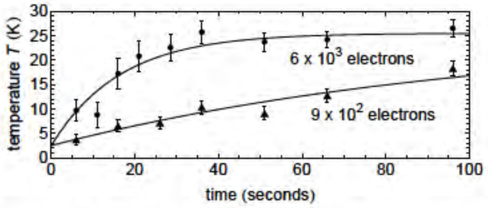


Figure 8: Only 10^3 embedded e^- can heat (or cool) 10^6 $\overline{\mathrm{p}}$ to 25 K.

2.2.7 First $\overline{\mathrm{p}}$ Adiabatic Cooling and the Lowest Measured $\overline{\mathrm{p}}$ Plasma Temperature
– Phys. Rev. Lett. 106, 073002 (2011)

Adiabatic cooling takes place when a system of particles is allowed to expand its volume. This is done for $\overline{\mathrm{p}}$ in a trap by reducing the depth of the potential well that confines them [35]. Fig. 9 shows the measured $\overline{\mathrm{p}}$ temperature ss a function of the axial oscillation frequency for trapped $\overline{\mathrm{p}}$ (a measure of the trap well depth) at the intial point where embedded e^- brought the $\overline{\mathrm{p}}$ plasma to the 25 K equilibtrium value discussed above.

When the well depth is reduced enough we observe a $\overline{\mathrm{p}}$ temperature of $3.5 \pm 0.7K$ (the gray band in Fig. 9).

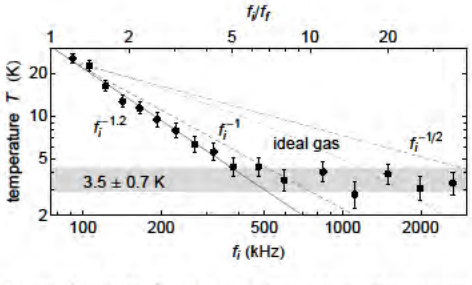


Figure 9: Adiabatic cooing of antiprotons.

This temperature after adiabatic cooling is the lowest $\overline{\mathrm{p}}$ plasma temperature ever observed. The temperature could be even lower since we cannot rule out the possibility that the gray band represents the lowest temperature that our method can measure, rather than the actual $\overline{\mathrm{p}}$ plasma temperature. During the next grant period, one goal is to use adiabatically-cooled $\overline{\mathrm{p}}$ to produce trappable $\overline{\mathrm{H}}$.

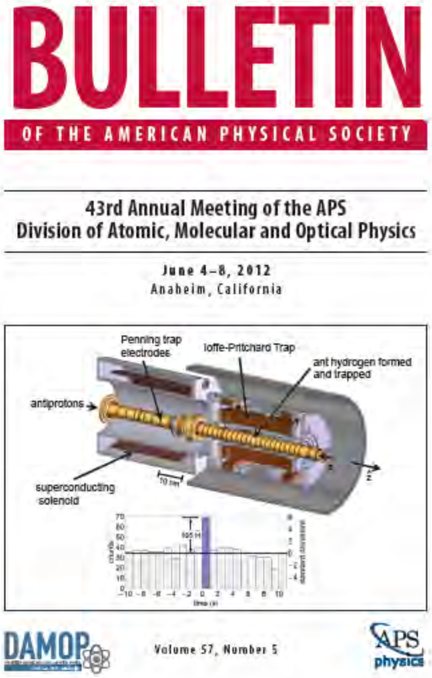
2.2.8 Trapped Antihydrogen in Its Ground State

– Phys. Rev. Lett. 108, 113002 (2012)
– Phys. Rev. A 87, 023422 (2013)

The PI's proposal to use cold trapped $\overline{\mathrm{p}}$ and e^+ to form $\overline{\mathrm{H}}$ that is cold enough to be trapped in a superimposed Ioffe trap [22] was realized during the current grant period. ATRAP demonstrated 5 ± 1 simultaneously $\overline{\mathrm{H}}$ trapped in its ground state [36], while ALPHA demonstrated 0.7 ± 0.3 for comparable times [?].

ATRAP carried out the search for trapped $\overline{\mathrm{H}}$ atoms (reported as part of the first demonstration of $\overline{\mathrm{H}}$ production within a Penning-Ioffe trap [25]) (as mentioned on p. 7). We decided that our limit of less than 20 simultaneously trapped atoms per trial meant that interesting measurements required more simultaneously trapped atoms. We suspended our search for trapped $\overline{\mathrm{H}}$ atoms till we learned to increase the $\overline{\mathrm{p}}$ plasma size by more than a factor of 100, and also learned how to improve the interaction of the $\overline{\mathrm{p}}$ and e^+ plasmas. Meanwhile, ALPHA moved directly to searching for smaller numbers of simultaneously trapped $\overline{\mathrm{H}}$.

Our 5 ± 1 atoms per trial compares very favorably to the 0.7 ± 0.3 atoms trapped per trial for comparable times by ALPHA [?]. However, given that we developed the capability to use more than 100 times more $\overline{\mathrm{p}}$ per trial, our observed number of trapped $\overline{\mathrm{H}}$ atoms did not scale up in proportion. We were naturally disappointed, but we are encouraged by the slow but sure way that we are learning to scale up the production of trapped $\overline{\mathrm{H}}$ atoms as we learn to more effectively control and manipulate the large $\overline{\mathrm{p}}$ and e^+ plasmas.



BULLETIN
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Division of Atomic, Molecular and Optical Physics

June 4–8, 2012
Anaheim, California

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Figure 10: The ATRAP apparatus and the signal that reveals trapped, ground state $\overline{\mathrm{H}}$ atoms.

2.2.9 First One-Proton Demonstration that the $\overline{\mathrm{p}}$ Magnetic Moment Can be Measured 1000 Times More Precisely

– Phys. Rev. Lett. 104, 143001 (2010)
– Phys. Rev. Lett. 108, 153001 (2012)

Using a single trapped proton, suspended within an extremely strong magnetic bottle gradient and detected using a one-proton self-excited oscillator [37], we demonstrated the possibility to measure the proton magnetic moment in nuclear magnetons with a precision of 2.5 parts per million [38]. The proton cyclotron frequency and the proton's spin flip frequency, the two frequencies that together determine the proton's magnetic moment, are deduced from the two measured resonance lineshapes in Fig. 11. A similar but 3 times less precise measurement was more recently reported [39] by a team that includes W. Quint (a former postdoc in this AFOSR-sponsored research program).

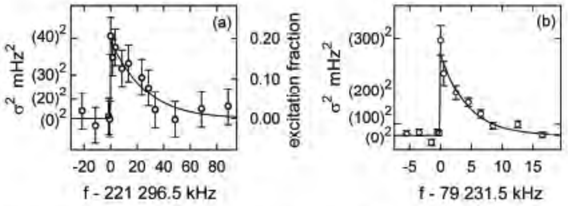

Figure 11: The cyclotron and spin lineshapes from which the corresonding resonance frequency and the magnetic moment are deduced.

The proton magnet moment is thereby measured more precisely than has been the $\overline{\mathrm{p}}$ magnetic moment by about a factor of 1000, as illustrated in Fig. 12. Unlike the hydrogen maser measurement that most precisely determines the proton magnetic moment so far, the one-trapped-proton method should work as well with a $\overline{\mathrm{p}}$ as with a p – once an antiproton is loaded into suitable trap.

This development was encouraging enough that we shipped our apparatus to ATRAP's precision measurement beamline to attempt to realize a 1000-fold improved $\overline{\mathrm{p}}$ magnetic moment yet this year. The $\overline{\mathrm{p}}$ effort, discussed on p. 16, will be an central effort for the next grant period.

After the $\overline{\mathrm{p}}$ run is over for the year we will continue making progress with a single proton. Once we are able to observe a single spin flip of a single $\overline{\mathrm{p}}$ or p then we should be able to make an even better improved precision. A realistic goal seems to be improving the comparison of the $\overline{\mathrm{p}}$ and p magnetic moments by a factor of 1 to 10 million – a very large precision increase for such a fundamental constant.

2.2.10 First One-Particle Comparison of the $\overline{\mathrm{p}}$ and p Magnetic Moments – Phys. Rev. Lett. 110, 130801 (2013)

Upon completing proton magnetic moment measurement early in 2012 [38] we modified our proton apparatus to accept $\overline{\mathrm{p}}$ (Fig. 20). Three students took this apparatus to CERN. It was a heroic effort given that only a few months of CERN antiprotons were available before CERN shutdown to repair its Large Hadron Collider. Fortuenately, it succeeded.

The first single-particle measurement of the $\overline{\mathrm{p}}$ magnetic moment resulted in a 4.4 ppm determination – 680 times more precise than realized with exotic atoms [40]. The big increase in precision follows 20 years that saw no increase in precision, as represented in Fig. 12. The methods and apparatus were initially demonstrated in a one-proton measurement of the p magnetic moment [38], following the realization of feedback cooling and a self-excited oscillator with one proton [37].

The resulting comparison of the antiproton and proton magnetic moments is

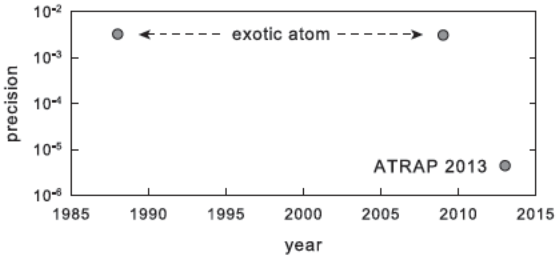

Figure 12: After 20 years with no improvement, the comparisons of the $\overline{\mathrm{p}}$ and p magnetic moments were compared 680 times more precisely in the first one-particle measurement of these moments.

$$\mu_{\overline{\mathrm{p}}}/\mu_p = \quad -1.000\,000 \quad \pm 0.000\,005 \quad [5.0\ \mathrm{ppm}] \tag{1}$$

$$\mu_{\overline{\mathrm{p}}}/\mu_p = \quad -0.999\,999\,2 \quad \pm 0.000\,004\,4 \quad [4.4\ \mathrm{ppm}], \tag{2}$$

consistent with the prediction of the CPT theorem. The first uses the proton moment directly measured within the same trap electrodes [38]. The second uses the more precise proton moment deduced indirectly from three measurements (not possible with $\overline{\mathrm{p}}$) and two theoretical corrections [41, 42].

2.2.11 Observation of a One-Proton Spin Flip – Phys. Rev. Lett. 110, 140406 (2013)

Quantum jump spectroscopy of a single trapped electron shows that a magnetic moment can be measured much more precisely, to 3 parts in 10^{13} [43]. Individual spin transitions have now been resolved [44], as needed to determine the needed spin precession frequency. For the substantially smaller nuclear moments of the $\overline{\mathrm{p}}$ and p this is much more difficult. The first observation of individual spin transitions and states for a single p in a Penning trap, with a method applicable for a $\overline{\mathrm{p}}$, is illustrated in Fig. 13,. A high 96% fidelity is realized by selecting a low energy cyclotron motion from a thermal distribution, by saturating the spin transition, and by careful radiofrequency shielding. The modest spin state detection efficiency realized in this initial demonstration could be used to make a magnetic moment measurement.

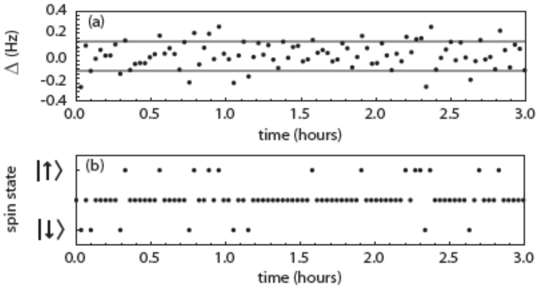

Figure 13: (a) Three hour sample of measured frequency shifts. (b) Corresponding identifications of spin states. Points between the heights of the identified spin states indicate that no spin state identification could yet be made.

However, it now seems possible to use adiabtic passage to detect the spin state in every detection attempt to decrease the measurement time. The possibility to measure a $\overline{\mathrm{p}}$ cyclotron frequency (the other frequency needed to determine the moment) has been demonstrated to 1 part in 10^{10} [17] to compare the charge-to-mass ratios of the $\overline{\mathrm{p}}$ and p [17]. With the spin method demonstrated here, it may be possible to approach this precision in comparing the $\overline{\mathrm{p}}$ and p magnetic moments to make an extremely precise test of the CPT theorem with a baryon.

2.3 Near Term and Longer Term Program

The accomplishments for the current grant period (above) are steps toward mentioned goals for the next grant period. Additional and longer term goals are summarized in this section after a short overview of the current ATRAP capability and apparatus,

2.3.1 ATRAP Overview

The ATRAP $\overline{\mathrm{p}}$ and $\overline{\mathrm{H}}$ experiments are larger than many AMO experiments – too large to get all the apparatus in the picture of Fig. 14, but much smaller than typical particle physics experiments at CERN. ATRAP has 3 experimental zones, each the size of a small room. The first, for e^+ accumulation (near right), contains the three traps of the e^+ accumulator. the massive (orange) solenoid that surrounds them, and a highly shielded radioactive source that provide e^+ to be slowed and accumulated. The second contains a superconducting solenoid for $\overline{\mathrm{p}}$ magnetic moment and mass measurements (back, right of center). The third is for $\overline{\mathrm{H}}$ studies (left of center). AD $\overline{\mathrm{p}}$ are directed vertically upward into both the second and third zones.

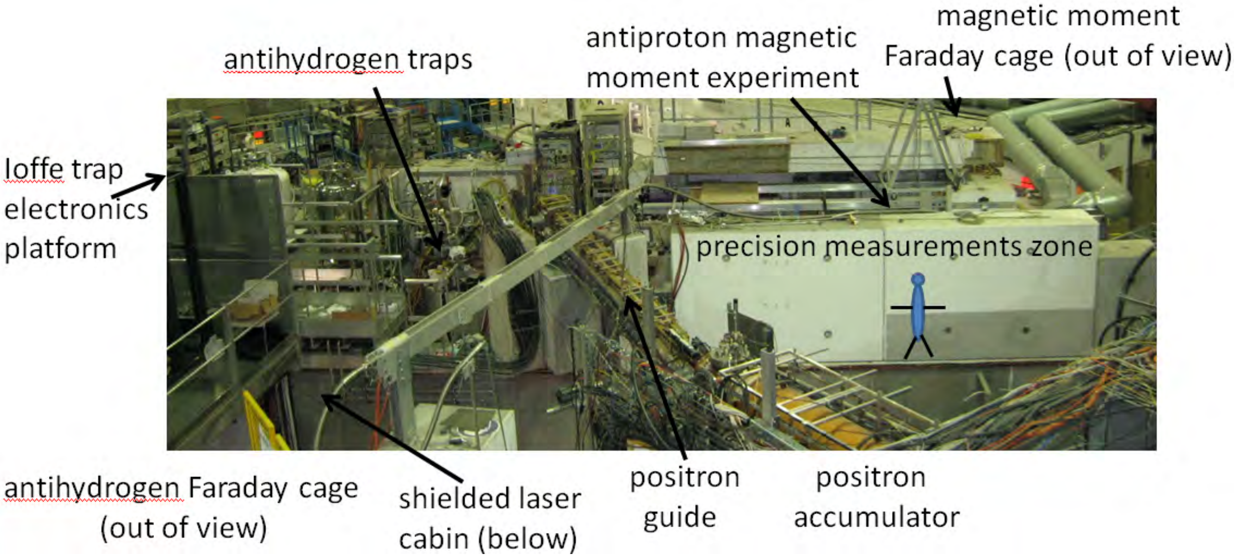

Figure 14: Photograph of the three experimental zones of ATRAP at CERN.

A simplified overview of the ATRAP $\overline{\mathrm{H}}$ apparatus is in Fig. 15. The solenoid, dewars, detectors, and particle paths for the $\overline{\mathrm{H}}$ trap apparatus are in Fig. 16, with representations of the Penning trap electrodes and the Ioffe trap coils in Fig. 17.
Out of view are two small room-size Faraday cages – each containing many racks of sensitive electronics for the $\overline{\mathrm{H}}$ and precision measurement experiments, respectively. Also not in view is a shielded laser cabin that is

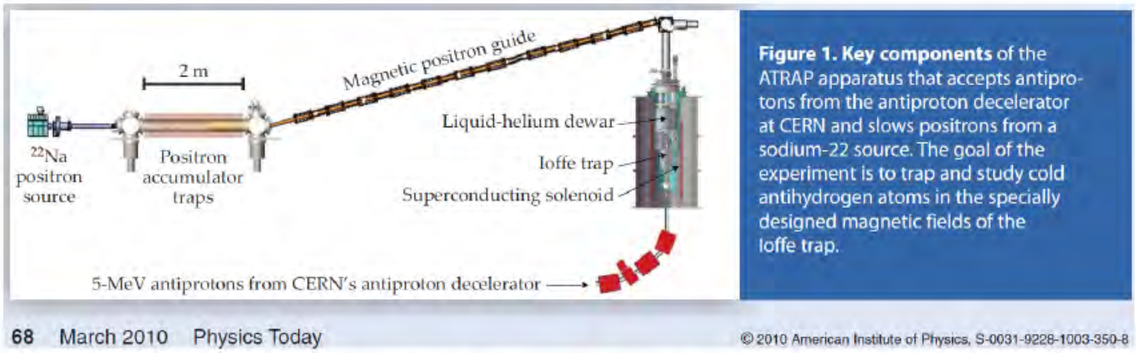

Figure 1. Key components of the ATRAP apparatus that accepts antiprotons from the antiproton decelerator at CERN and slows positrons from a sodium-22 source. The goal of the experiment is to trap and study cold antihydrogen atoms in the specially designed magnetic fields of the Ioffe trap.

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Figure 15: Overview of the ATRAP antihydrogen apparatus.

large enough for two laser tables and a work area, and a large barrack that contains tools, desks and control computers. (After this year the barrack will be relocated about 100 meters away to reduce radiation exposure for personnel.)

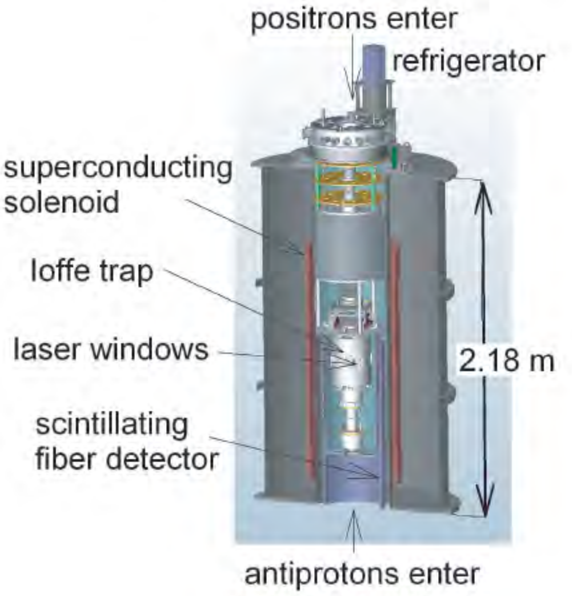

Figure 16: Cutaway view of the ATRAP $\overline{\text{H}}$ trap apparatus. The positron accumulator, magnetic positron guide, Faraday cage, and about 12 racks of electronics are not shown.

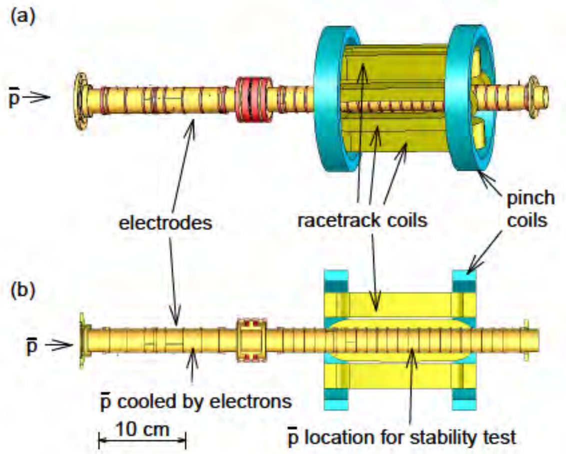

Figure 17: Three dimensional (a) and cross section (b) views of the 45 cylindrical Penning trap electrodes and the Ioffe trap (first generation), rotated by 90 degrees with respect to Fig. 16.

2.3.2 Second Generation Penning-Ioffe Trap

Overview

A second generation Ioffe trap has been constructed, with initial tests hopefully to be completed this fall. Fig. 18 contrasts the cross section and the trap characteristics of our first and second Ioffe traps, for a 1 T bias field out of the page in (a) and (b). The new trap offers several important advantages over our first generation Ioffe trap (Figs. 16-17).

1. The flexible new trap includes both a quadrupole Ioffe trap (four current bars) and an octupole Ioffe trap (eight current bars). The $\overline{p}$ and e^+ can be loaded and manipulated to form $\overline{\text{H}}$ in the lower field gradient of an octupole trap [45], with $\overline{\text{H}}$ then pushed more on axis and into contact with the cooling and spectroscopy lasers within a quadrupole trap.

2. Very low inductance and eddy currents should make it possible to turn off a magnetic trap in 10 ms whenever desired, rapidly enough to allow distinguishing the annihilation of liberated $\overline{\mathrm{H}}$ atoms from essentially all detector background counts. (The first generation Ioffe trap, designed to be turned off in 10 minutes, had to be quenched to turn it off in 1 s, and this could only be done once or twice per 8 hour shift.)

3. Construction on a epoxy fiberglass form has potential detection advantages for observing where $\overline{\mathrm{H}}$ formation is taking place, as well as suppressing eddy currents in the form that supports the coils.

4. The Penning trap electrodes within the new Ioffe trap are shaped to allow better manipulation of the very large plasmas that we can now make available for $\overline{\mathrm{H}}$ production, and the even larger $\overline{\mathrm{p}}$ plasmas that should be available after the ELENA upgrade.

Disaster

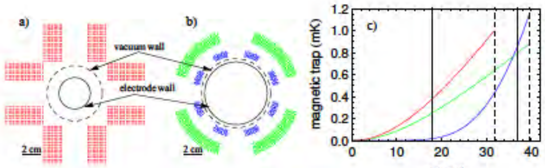

Figure 18: Cross section of the first (a) and second (b) generation quadrupole Ioffe trap, with a comparison of their radial well depths (c).

The construction of this trap has required a lot more time and effort from us than we expected. The company contracted to build this trap (the only company in the world that we could find able to embed the superconducting windings within grooves in a an epoxy coil form) failed to form a robust vacuum enclosure. We were thus forced to take on the construction of a G-10 vacuum enclosure. After 3 full-size prototypes were successful, we built and assembled the "final" vacuum enclosure. Unfortunately, when we cooled this down to helium temperature we were unable to control the thermal gradients during the cooing, and the vacuum system failed.

We lost about two years when the year of preparation and assembly are added to the year of dismantling, redesign and reassembly. It was very painful for our ATRAP team.

Recovery

During the year that CERN was closed to repair its Large Hadron Collider (LHC), we cut the Ioffe trap out of the failed epoxy-fiberglass vacuum system, designed a new metal enclosure, demonstrated that the Ioffe trap still performed electrically as it was designed to perform, fabricated the new enclosure, and assembled it. The new vacuum enclosure (Fig. 19) was constructed of a not-very-common alloy of Ti that retains its resistivity at low temperature to reduce eddy currents. As this is written, the completed Ioffe trap is being prepared for commissioning with antiprotons in the fall of 2014.

It is worth noting that this trap has side windows that will facilitate laser cooling of trapped antihydrogen atoms – unlike other traps intended for antihydrogen atoms. The trap difficulties would not have happened except for our determination to provide these ports.

2.3.3 Demonstrating Laser Cooling of Trapped Antihydrogen Atoms

Demonstrating that the newly available trapped $\overline{\mathrm{H}}$ atoms in their ground state can be laser cooled is an important priority, since this is an essential step towards interesting laser spectroscopy. With $\overline{\mathrm{H}}$ atoms in the second generation Ioffe trap, it should be possible to observe changes in the energy spectrum of the trapped atoms due to changes in the frequency and strength of a coherent source of Lyman alpha radiation.

Figure 19: The leak tight Ti vacuum enclosure within which the low inductance Ioffe trap is located, with Eric Tardiff (the postdoc who championed this very difficult project) and the PI.

ATRAP has invested a lot of effort in providing laser access to the trapped $\overline{\mathrm{H}}$ through the sides of our Penning Ioffe trap, as well as along the axis. The Ioffe trap windings are shaped to allow laser access between the racetrack coils. Cryogenic windows that transmit UV at 121 nm and reliably withstand temperature cycling by hundreds of degrees have been demonstrated.

ATRAP has also invested heavily in a continuous source of Lyman alpha radiation at 121 nm. Starting in the Hänsch Laboratory in Garching, and then moving to the Walz Laboratory in Mainz, our collaborators continue to improve a source of Lyman alpha radiation suitable for laser cooling and for 1s-2p spectrosocpy [46, 47, 48, 49, 50, 51, 52, 53, 54, 55]. Four-wave mixing is used to generate continuous, coherent Lyman alpha radiation at 121.5 nm.

Up to 6 μW of coherent UV light near to the Lyman alpha frequency was recently reported using triply resonant four-wave mixing [54], and the robustness of the source continues to improve. Enough power to cool trapped $\overline{\mathrm{H}}$ and for initial $\overline{\mathrm{H}}$ spectroscopy [19] has already been demonstrated. This is a a unique ATRAP capability so far.

2.3.4 Antihydrogen Spectroscopy Progression

We must succeed eventually with accurate 1s - 2s spectroscopy for these experiments to be successful. Space does not permit reviewing the possibility to do the spectroscopy of 100 to 1000 $\overline{\mathrm{H}}$ atoms as has been proposed [8].

The laser spectroscopy of $\overline{\mathrm{H}}$ will go in steps of increasing precision and decreasing sensitivity. The initial focus will be upon simply observing an optical signature of $\overline{\mathrm{H}}$. As we progress, our apparatus will be increasingly optimized and our technique will be increasingly refined. With greater sensitivity we will be able to use laser transitions which offer greater spectroscopic precision at the cost of less signal.

1. Lower excited states can be excited to states that can be field ionized for efficient detection, with a CO_2 laser exciting an $n = 10$ state, and a TiSaph laser exciting from $n = 3$, for example.
2. Use the continuous coherent Lyman α source do laser spectroscopy of the $\overline{\mathrm{H}}$ 1s - 2p. The sensitivity will be high as required for spectroscopy with not so many atoms, but the resolution will be severely limited by the Doppler shift and by the rapid decay of the 2p states.
3. A nearly resonant 2-photon process will allow a sensitivity which is comparable, but with a much better resolution. The first photon is nearly resonant with Lyman α $(1s - 2p)$, while the second is nearly resonant with $2p - 3s$ or $2p - 3d$. The $n = 3$ levels live approximately 100 times longer than the 2p levels and this gives a resolution which is improved by this factor.
4. Finally we would be ready to try 1s - 2s spectroscopy, possibly with as few as 100 atoms [8], or less, using two photons to drive the transition, and a third to ionize the atom for annihilation detection. This is most difficult and is the ultimate goal.

Our approach differs from those who will try to go immediately to 1s - 2s spectroscopy. We fear that even with reasonable amounts of power we would waste much time with no signal, or we would need to use a very intense pulsed laser which would dissipate an unacceptably large power in our cryogenic system, and the development of which would not advance our spectroscopic goals.

2.3.5 Preparing the Cavities and Lasers for 1s-2s Spectroscopy

During the next grant period we will build up a laser system for two photon 1s-2s spectroscopy of $\overline{\mathrm{H}}$. The design of this laser system is based upon the system [56] developed for the most precise 1s-2s spectroscopy of H [9]. We are grateful for the guidance of our long time advisers in the Hänsch and Udem group in Garching, renowned for their H spectroscopy. A laser at 972 nm will be locked to a state-of-the-art ULE cavity, and then doubled twice. The frequency of the cavity-stabilized laser will be measured crudely with a wavemeter and then precisely with a fiber comb locked to the atomic clocks in the GPS system to measure the cavity frequency and drift in time.

2.3.6 Building on 100 Times More $\overline{\mathrm{H}}$ Atoms Produced by Laser-Controlled Charge Exchange

ATRAP demonstrated that $\overline{\mathrm{H}}$ could be produce by a two-step, laser-controlled charge exchange process [57]. This process has possible advantages over the three-body formation in a nested Penning trap [23] in that the lasers control the excitation state of the $\overline{\mathrm{H}}$ that is formed, and by offering $\overline{\mathrm{H}}$ kinetic energies as cold (or hot) as the $\overline{\mathrm{p}}$ from which the $\overline{\mathrm{H}}$ forms. The number of atoms produced in the demonstration was so small, however, that we suspended work on this approach until we could use much larger plasmas of e^+ and $\overline{\mathrm{p}}$.

With the much larger plasmas realized during the current grant period (discussed above) we returned to this process. So far we have managed to produce more than a 100 times more Rydberg positronium and $\overline{\mathrm{H}}$

atoms. Adiabatic cooling has not yet been incorporated and we have not had the time to make a significant effort to trap $\overline{\mathrm{H}}$ atoms produced by this process. We hope to publish an account of the progress soon, and to investigate how much $\overline{\mathrm{H}}$ can be trapped when the second generation Ioffe trap is on line.

2.3.7 Seeking an Additional 10^4 Improved Precision in the $\overline{\mathrm{p}}$ Magnetic Moment

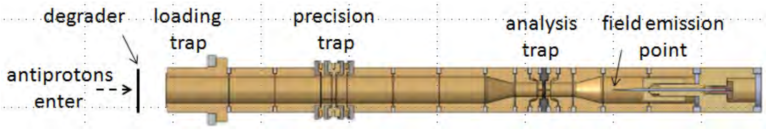

Figure 20: First traps being used to use single particle methods to measure the $\overline{\mathrm{p}}$ magnetic moment.

Hopes are high for a greatly improved comparison of the magnetic moments of the antiproton and proton since we managed make the first one-particle comparison [38, 40] and then to detect the spin flips of a trapped proton [44] (as discussed). It should also be possible to make the new apparatus capable of a measurement of q/m for the $\overline{\mathrm{p}}$ that improves significantly our 9 parts in 10^{11} measurement [17] - currently the best baryon CPT test. The $\overline{\mathrm{p}}$ magnetic moment measurement, as well as a q/m measurement, can be done in parallel with $\overline{\mathrm{H}}$ studies in the separate location and beamline we have available to occasionally load a $\overline{\mathrm{p}}$. We have demonstrated in the past a vacuum that is good enough so that experiments with a single $\overline{\mathrm{p}}$ can go on for days to months without the need to reload a $\overline{\mathrm{p}}$.

A new collaboration with proton experience [39] (including W. Quint, a former postdoc in this research program) has formed to compete on measuring the $\overline{\mathrm{p}}$ moment. They declined our invitation to join forces for our 2012 measurements and beyond.

2.3.8 Profiting and Preparing for the ELENA Upgrade to the CERN AD

When the PI started low energy $\overline{\mathrm{p}}$ and $\overline{\mathrm{H}}$ physics program at CERN, the $\overline{\mathrm{p}}$ came from CERN's Low Energy Antiproton Ring (LEAR – a storage ring loaded from two other CERN storage rings. When the three rings were shut down for financial reasons, CERN's Antiproton Decelerator (AD) was built to allow the low energy $\overline{\mathrm{p}}$ and $\overline{\mathrm{H}}$ physics to continue. Four other collaborations (soon to be five) have since joined us in the low energy $\overline{\mathrm{p}}$ and $\overline{\mathrm{H}}$ quest.

The AD delivers a pulse of about 3×10^7 $\overline{\mathrm{p}}$ to one experiment every 100 seconds. From a single $\overline{\mathrm{p}}$ pulse we capture about 1 in 10^3 in our Penning trap. Since the AD does not switch rapidly between experiments, the various collaborations take a 8 hour shifts, rotating the time of day for these shifts week by week. The rotation shift schedule is hard on personnel and productivity.

The CERN management recently approved the construction of an ELENA upgrade – a low energy storage ring to slow and electron-cool the $\overline{\mathrm{p}}$ to 100 keV before sending them to experiments. All magnetic beam lines currently delivering $\overline{\mathrm{p}}$ to experiments will be replaced with low energy, electrostatic lines. ELENA is a critical upgrade for two reasons.

1. We should be able to trap about 100 times more $\overline{\mathrm{p}}$. This will significantly increase the rate at which we can make measurements (extremely slow at present).

2. ELENA will be able to send $\overline{\mathrm{p}}$ to each of the experiments every 100 s (rather than to only 1 experiment for 8 hours). This means that we can run 24 hours per day – tuning up and setting up a set of measurements by day and then taking data all night mostly under computer control. (This is how we take data for all of our successful precision measurements at Harvard.) The 8 hour shifts at different times each week will cease to be.

A significant challenge is that our apparatus must be adapted to allow 100 keV $\overline{\mathrm{p}}$ to enter our traps. Vacuum windows that pass $\overline{\mathrm{p}}$ at this energy are too thin to support any substantial pressure difference across them. We thus need to change the way that we slow the $\overline{\mathrm{p}}$, admit them into our nearly perfect trap vacuum, and tune their energy to maximize the number of $\overline{\mathrm{p}}$ that have extremely low energies along the axis of the magnetic field of the Penning traps. We have yet to design and construct the items needed to so modify our apparatus.

2.4 Conclusion

How does one conclude the description of an admittedly adventuresome antihydrogen research program that involves so many experimental techniques and so many sub-fields of physic? The challenges that remain are daunting, perhaps enough to make one abandon the adventure if we had not already come so far. The steady progress of the last five years seems likely to continue thanks to the tireless and intense efforts of the excellent postdocs, graduate students and undergraduates who use the antihydrogen quest to learn the experimenter's art, supported by the lively interest, experience and contributions of a large and growing physics community.

2.5 Principle Investigator Time

The PI is actively and continuously involved in this antiproton and antihydrogen research program. He personally supervises all students and postdocs, and leads the team. He is on call at all times of the day and night. The only source of low energy antiprotons is the CERN laboratory in Geneva, Switzerland. When antiprotons are available (about half of each year) he travels to CERN nearly every week. (The other personnel supported by this research program live in Geneva for most of the year.) He has cell phones in Geneva and in the US. He and his team use IP phones which allow very inexpensive phone communications between the US and Switzerland. There is also a weekly video meeting between the PI, the personal at CERN, and other collaborators. This video connection is also used whenever needed to facilitate ready communication between the PI and others involved in the experiment. All logbooks for the experiment are online so that the PI can read them and enter comments, as can any other member of the ATRAP team.

From the very first funding of this antiproton research program about twenty years ago, AFOSR and NSF have jointly provided the support. If it were not so this program would not have been possible. NSF continues to support this research, but the atomic, molecular and optical physics program which supports this research is also (like AFOSR) not able to provide the level of support required to do overseas research. Despite the highly leveraged nature of this project (with CERN providing storage rings, operators, and antiprotons free of charge to a US led team) it is very expensive to do research work overseas because of the high travel and shipping cost. In addition, the apparatus must also be engineered better than is required in a home laboratory owing to the need for it to always be ready when antiprotons are available. The AFOSR support, primarily for personnel to work on the experiment, is crucial. The details are provided in the "Current and Pending Support" section.

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8. "Efficient Transfer of Positrons from a Buffer-Gas-Cooled Accumulator into an Orthogonally Oriented Superconducting Solenoid for Antihydrogen Studies", D. Comeau, A. Dror, D.W. Fitzakerley, M.C. George, E.A. Hessels, C.H. Storry, M. Weel, D. Grzonka, W. Oelert, G. Gabrielse, R. Kalra, W.S. Kolthammer, R. McConnell, P. Richerme, A. Mullers, and J. Walz. New J. Phys. **14** 045006 (2012).
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11. "Electric Fields Prevent Mirror-Trapped Antiprotons in Trapped Antihydrogen Studies", P. Richerme, G. Gabrielse, S. Ettenauer, R. Kalra, E. Tardiff, D.W. Fitzakerley, M.C. George, E.A. Hessels, C.H. Storry, M. Weel, A. Müllers, and J. Walz, Phys. Rev. A **87**, 023422 (2013).
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14. "Electron Cooling and Accumulation of 4×10^9 Positrons in a System for Longterm Storage of Antihydrogen Atoms", D.W. Fitzakerley, M.C. George, E.A. Hessels, C.H. Storry, M. Weel, D. Grzonka, W. Oelert, S. Ettenauer, G. Gabrielse, R. Kalra, E. Tardiff, A. Müllers, and J. Walz (submitted for publication).

1.

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Gerald Gabrielse

Program Manager
The AFOSR Program Manager currently assigned to the award

Tatjana Curcic

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Reporting Period End Date

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Abstract

A matter particle and its antimatter particle annihilate upon colliding. All of their respective masses are transformed quickly into energy. Antihydrogen atoms have been produced and suspended within a "container with no walls." Antihydrogen atoms, the simplest atoms made entirely of antimatter, were suspended and held in a Ioffe trap, at a magnetic field minimum. This proof-of-principle demonstration suggests that many more antimatter atoms could be confined in an improved Ioffe trap, and that these could be laser cooled as needed to use precise laser spectroscopy to study their properties with high precision.

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Archival Publications (published) during reporting period:

"Centrifugal Separation of Antiprotons and Electrons"
G. Gabrielse, W.S. Kolthammer, R. McConnell, P. Richerme, J. Wrubel, R. Kalra, E. Novitski, D. Grzonka, W. Oelert, T. Sefzick, J.S. Borbely, D. Fitzakerley, M.C. George, E.A. Hessels, C.H. Storry, M. Weel, A. Mullers, J. Walz, A. Speck,
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Nucl. Inst. and Meth. A, 640, 232 - 240 (2011).

"Trapped Antihydrogen in Its Ground State"
G. Gabrielse, R. Kalra, W. S. Kolthammer, R. McConnell, P. Richerme, D. Grzonka, W. Oelert, T. Sefzick, M. Zielinski, D. W. Fitzakerley, M. C. George, E. A. Hessels, C. H. Storry, M. Weel, A. Müllers, and J. Walz,
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"Efficient transfer of positrons from a buffer-gas-cooled accumulator into an orthogonally oriented superconducting solenoid for antihydrogen studies"
D. Comeau, A. Dror, D. W. Fitzakerley, M. C. George, E. A. Hessels, C. H. Storry, M. Weel, D. Grzonka, W. Oelert, G. Gabrielse, R. Kalra, W. S. Kolthammer, R. McConnell, P. Richerme, A. Müllers, and J. Walz,
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W. Steven Kolthammer, Harvard Ph.D. Thesis (September, 2011).

Thesis Supervised (31): "Trapped Antihydrogen in Its Ground State",
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Thesis Supervised (32): "First Single Particle Measurements of the Proton and Antiproton Magnetic Moments",
Jack DiSciacca, Harvard Ph.D. Thesis (May 7, 2013).

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None

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None

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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