15 January 2013

The Production and Study of Cold Antihydrogen

2012 Progress Report by the Antihydrogen TRAP Collaboration (ATRAP)

CERN-SPSC-2013-007 / SPSC-SR-114
14/01/2013

G. Gabrielse[1], **J. DiSciacca, S. Ettenauer, K. Marable, M. Marshall, E. Tardiff, R. Kalra**
Department of Physics, Harvard University, Cambridge, MA 02138 USA

Walter Oelert, Dieter Grzonka, Thomas Sefzick, Marcin Zielinski
Institut für Kernphysik, Forschungszentrum Jülich, Germany

Eric Hessels, Cody Storry, Daniel Fitzakerley,
Matthew George, Matthew Weel
Department of Physics and Astronomy, York University,
Toronto, Ontario, M3J 1P3, Canada

A. Müllers[2], **J. Walz**[2]
Institute für Physik, Johannes Gutenberg Universität Mainz, D55099, Mainz, Germany

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[1] spokesperson,gabrielse@physics.harvard.edu

[2] antihydrogen studies only

A. Antiproton Magnetic Moment Aspirations and Accomplishments

The part of the ATRAP effort that is focussed upon precision measurements with a single antiproton (magnetic moment and charge-to-mass ratio) may be less familiar to the SPSC since they mostly took place off site with a proton. This year our notable accomplishment was in making the first one-particle measurement of the antiproton magnetic moment, achieving a 680 times more precise measurement than had been realized with any other method.

1. ATRAP from the beginning has had two antiproton beam ports. The first one (we call zone 1) is for precision measurements with antiprotons – of the magnetic moment and the charge-to-mass ratio. The second (we call zone 2) is for antihydrogen experiments.
2. In every ATRAP report to the SPSC since ATRAP's beginning we have summarized the progress towards measuring the antiproton magnetic moment. This progress took place away from CERN for many years because it took many years to develop the apparatus and method that was needed to measure the antiproton magnetic moment using a new method.
3. In last year's ATRAP report we reported that we had just managed (with a proton) to demonstrate a method for measuring the antiproton 1000 times more accurately antiproton magnetic moment [1]. I reported this to the SPSC. Given this demonstration away from CERN, We said that we were strongly considering if it would be possible to modify the apparatus to accept antiprotons, move many crates of apparatus to CERN from Harvard, solve the additional noise challenges that CERN presents to a precision measurement, and make the measurement.
4. Not long after the SPSC meeting ATRAP decided officially to take the considerable risk and push the antiproton magnetic moment measurement very hard during 2012. Besides what has already been mentioned, it was necessary to reestablish the vacuum system connecting to the AD, recommission detectors that had not been used for many years, energize the second superconducting magnet that had not been energize for some years, steering the antiproton beam, working with CERN to develop a method to switch rapidly between the two ATRAP zones, etc. (Because they were part of an independent effort to make a magnetic moment measurement the Mainz members of our team did not participate the ATRAP magnetic moment measurement.)
5. One factor in the ATRAP decision to push this very hard in 2012 was that no antiprotons would be available at CERN for 1.5 years (or more). It was important to try the antiproton magnetic moment measurement before the shut down even if the experiment did not succeed to see what additional challenges to making this precision measurement were presented by the electrically and magnetically noisy CERN environment.
6. Another factor in the ATRAP decision to push the magnetic moment measurement very hard in 2012 was that we thought that if ATRAP succeeded in making a huge improvement in the magnetic moment precision that this would be good for ATRAP and for the AD program, given that there were not likely to be other such accomplishments at ATRAP or at the AD this year.

Precision magnetic moment measurements have always been an open part of the ATRAP program. The ATRAP beamline was constructed with this in mind. The SPSC has always encouraged this. We have always reported our progress. I hope that the SPSC is delighted with this ATRAP accomplishment and celebrates it in its report as being very good for the AD program as well as for ATRAP. The antiproton magnetic moment measurement and result are in an attached 4 page manuscript submitted to Physical Review Letters.

B. Antihydrogen Aspirations and Accomplishments

The proposal to make cold antihydrogen using cold, trapped antiprotons was written down by some of us back in 1987 [2], not long after our TRAP collaboration trapped the first antiprotons [3]. The production of antihydrogen cold enough to capture in a neutral particle trap for precise laser spectroscopy was also proposed at the same time.

The basic antiproton methods now used by all antihydrogen collaborations were subsequently developed by the TRAP collaboration which evolved into ATRAP. Antiprotons were slowed in matter and trapped with the sudden application of a potential [3]. The antiprotons were then cooled with electrons to produce antiproton energies about 10^{10} times lower than had previously been produced. Antiproton accumulation (called stacking) was demonstrated soon after [4] and later reported in detail [5]. CERN's Antiproton Decelerator(AD) was built so that the antihydrogen aspirations could be realized. Three, soon to be four, collaborations now are approved by the SPSC for antihydrogen experiments.

Last year ATRAP reported the observation of 5 antihydrogen atoms per trial in the 2011 beam run [6]. The next clear goal is to laser cool trapped antihydrogen atoms. Doing this most effectively requires a Penning-Ioffe trap which has sideports (perpendicular to the magnetic field direction on axis) to admit coherent Lyman alpha radiation at 121 nm into the trap. Our first generation Ioffe trap was the first to have such openings into a antihydrogen trap, but this trap could only be used for a trial or two during an 8 hour beam shift. Our second generation trap was designed to have side ports and the capacity to be used repeatedly during a beam shift. To make reasonable progress we require the second generation trap.

At the time of the SPSC meeting last year, the new Ioffe-Penning trap apparatus was nearly ready to cool down so that it could be thoroughly tested before the 2012 antiproton run that started in May. An enormous amount of financial and personnel resources had been expended and we were looking forward to commissioning and using the trap in 2012. Unfortunately, despite the heroic efforts all year, we suffered two serious setbacks from which we haven not yet recovered. Here are the steps.

1. There was a failure of titanium to silver welds deep within the apparatus. This was very surprising since we had worked out the method to do this successfully with a company some years before, and such welds are fairly common in the TRAP apparatus. After taking the whole apparatus apart we traced the problem to a new welder in the company who had not done the developed procedure correctly. The welds were done just well enough so that they did not fail until cold cycled to helium temperature several times on average. After waiting for the welder we had worked with before to come out of the hospital and recover from his abdominal surgery (I really was talking to him in his hospital room), this problem was fixed. The whole apparatus was reassembled.

2. Despite the three full scale mockups of the Ioffe trap vacuum system that had worked, our G10-epoxy vacuum system for the new Ioffe trap failed when it was cycled to 4 Kelvin. It seems now like the thermal mass of the Ioffe-trap winding (not in the test systems, of course) contributed to large enough thermal gradients that there were stresses on the vacuum joints that were not present in the mockups.

3. We disassembled the whole apparatus a second time, tried to repair the leaking joints without completely dismantling them, and then reassembled the whole apparatus. This we knew was not the best procedure, but it was the only one that gave us any chance of trying the new trap with antiprotons in 2012. The trap vacuum system again failed when cooled as feared.

4. After beam time in December we machined off the old vacuum system. We have designed a new vacuum enclosure made of metal. Test pieces that will be used shortly to test the weld

procedures are being fabricated now. We will be using the shutdown to rebuild and test the new vacuum system.

For the 25 years that we have been working at CERN we have been pushing new apparatus and methods at various technological boundaries. Most of these efforts have succeeded and the AD antihydrogen program relies on the methods that were developed. This Ioffe-Penning trap with side ports to allow laser cooling is very challenging. We succeeded in our first generation Ioffe trap but only with an apparatus that could not be cycled rapidly enough to attempt laser cooling. Our first effort to make an second generation apparatus with sideports and the ability to cycle rapidly did not succeed. We are very disappointed in our lack of antihydrogen progress this year but we still are optimistic.

Our goal for the antihydrogen part of the ATRAP effort for the next beam time is the same as for the last beam time. We want to trap antihydrogen atoms in a second generation Ioffe trap that can be used to laser-cool the trapped atoms. Laser cooling of trapped antihydrogen is the next major step anticipated for ATRAP.

C. Needs During the Long Stutdown

During the long shutdown at CERN we intend to make progress on the antiproton magnetic moment measurements (with a proton). We also hope to test the second generation Ioffe trap, install it in its new vacuum enclosure, and then test the completed Penning-Ioffe apparatus. During the shutdown we thus need:

1. Liquid helium.
2. Cooling water.
3. Electricity and access to the AD experiment area.
4. Internet and cell phone access.

D. Not the Usual CERN Experiment

The low-energy, high precision antihydrogen research differs substantially from the normal high energy particle and nuclear physics experiments that are practiced so successfully at CERN. Most CERN experiments are carefully crafted so that with a large number of particles delivered to an interaction region over some years, a signal of a particular interaction or particle will be established (or not) at a desired and predictable level of statistical accuracy.

Antihydrogen experiments, like most highly accurate low-energy experiments, are very different. Most of the experimental time is spent in inventing new techniques and methods that make it possible to see a signal at all. A long sequence of short experiments require very precise control and preparation, but the result of one short experiment helps decide what short experiments will follow it. Longer term time schedules are thus less predictable than is normal for CERN high energy experiments. Once a signal is found, the accuracy attained is rarely statistical, being generally limited by systematic uncertainties.

Many other examples can be given for extremely precise measurements being realized after considerable time and effort. One is that the extremely accurate hydrogen spectroscopy experiments by an ATRAP collaborator who was recognized with the 2005 Nobel prize [18]. The recent electron magnetic moment measurement and the fine structure constant measurement made recently by another in our collaboration is another example [19].

In the past, some on the SPSC committee have had difficulty understanding the difference between the high energy experiments that they are involved in at CERN, and this low energy antihydrogen research program. They have wanted time lines which show clearly and precisely what accuracy antihydrogen spectroscopy will be attained with what number of antiprotons delivered from the AD. It is important to realize that we spend most of our time at ATRAP inventing and refining new methods which eventually should make it possible to see and use an antihydrogen spectroscopy signal.

In some ways the situation is similar to the situation which pertained when the original TRAP Collaboration (PS196) proposed to accumulate antiprotons at an energy 10^{10} times lower than the lowest storage energy in the Low Energy Antiproton Ring, and to listen to the radio signal of a single antiproton as a way of the comparing antiproton and proton 45,000 time more accurately than had been done before. Despite the experience and expertise of the original collaboration, techniques demonstrated with matter particles had to be adapted for the very different circumstances under which antimatter particles were available. Most of the TRAP time and effort went into developing, demonstrating and improving apparatus and techniques, rather than into accumulating statistics with a fixed apparatus. There was some risk insofar as much had yet to be invented, but after a decade of concentrated effort by a small team, the ambitious goal was met and even substantially exceeded.

E. Relevant Publications for 2012

1. ATRAP, "Trapped Antihydrogen in its Ground State", Phys. Ref. Lett. **108**, 113002 (2012).
2. ATRAP members, "Direct Measurement of the Proton Magnetic Moment", Phys. Rev. Lett. **108**, 153001 (2012).
3. ATRAP, "Efficient Transfer of Positrons from a Buffer-Gas-Cooled Accumulator into an Orthogonally Oriented Supperconducting Solenoid for Antihdyrogen Studies", New J. Of Phys. **14**, 045006 (2012).
4. ATRAP members, "Triple Resonant Four-Wave Mixing Boosts the Yield of Continuous Coherent Vacuum Ultraviolet Genereration", Phys. Rev. Lett. **109**, 063901 (2012).
5. ATRAP, "A Semiconductor Laser System for the Production of Antihdyrogen", New. J. of Phys. **14**, 055009 (2012).
6. ATRAP, "Mirror-Trapped Antiprotons in Trapped Antihydrogen Studies", submitted to Phys. Rev. A.
7. ATRAP, "Electron Cooling and Accumulation of 4×10^9 Positrons in a System for Longterm Storage of Antihydrogen Atomes", submitted to Phys. Rev. A.
8. ATRAP, "One-Particle Measurement of the Antiproton Magnetic Moment", submitted to Phys. Rev. Lett.

Several other papers are in various stages of publication.

References

[1] J. DiSciacca and G. Gabrielse, Phys. Rev. Lett. **108**, 153001 (2012).

[2] G. Gabrielse, in *Fundamental Symmetries*, edited by P. Bloch, P. Pavlopoulos, and R. Klapisch (Plenum, New York, 1987), pp. 59–75.

[3] G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. L. Tjoelker, T. A. Trainor, H. Kalinowsky, J. Haas, and W. Kells, Phys. Rev. Lett. **57**, 2504 (1986).

[4] G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelker, J. Haas, H. Kalinowsky, T. A. Trainor, and W. Kells, Phys. Rev. Lett. **65**, 1317 (1990).

[5] G. Gabrielse *et al.*, Phys. Lett. B **548**, 140 (2002).

[6] G. Gabrielse *et al.*, Phys. Rev. Lett. **108**, 113002 (2012).

[7] G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelker, J. Haas, H. Kalinowsky, T. A. Trainor, and W. Kells, Phys. Rev. Lett. **63**, 1360 (1989).

[8] G. Gabrielse, S. L. Rolston, L. Haarsma, and W. Kells, Phys. Lett. A **129**, 38 (1988).

[9] D. S. Hall and G. Gabrielse, Phys. Rev. Lett. **77**, 1962 (1996).

[10] G. Gabrielse, D. S. Hall, T. Roach, P. Yesley, A. Khabbaz, J. Estrada, C. Heimann, and H. Kalinowsky, Phys. Lett. B **455**, 311 (1999).

[11] M. Amoretti, et al., Nature **419**, 456 (2002).

[12] G. Gabrielse *et al.*, Phys. Rev. Lett. **89**, 213401 (2002).

[13] G. Gabrielse *et al.*, Phys. Rev. Lett. **89**, 233401 (2002).

[14] G. Gabrielse *et al.*, Phys. Lett. B **507**, 1 (2001).

[15] G. Baur *et al.*, Phys. Lett. B **368**, 251 (1996).

[16] A. Speck, C. H. Storry, E. Hessels, and G. Gabrielse, Phys. Lett. B **597**, 257 (2004).

[17] C. H. Storry *et al.*, Phys. Rev. Lett. **93**, 263401 (2004).

[18] M. Niering *et al.*, Phys. Rev. Lett. **84**, 5496 (2000).

[19] D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008).