The ALPHA Experiment: A Cold Antihydrogen Trap

W. Bertsche[1,2], A. Boston[3], P.D. Bowe[4], C.L. Cesar[5], S. Chapman[1,2], M. Charlton[6], M. Chartier[3], A. Deutsch[1,2], J. Fajans[1,2], M.C. Fujiwara[7], R. Funakoshi[8], D.Gill[7], K.Gomberoff[1,2], D. Grote[2] , J.S. Hangst[4], R.S. Hayano[8], M. Jenkins[6], L. V. Jørgensen[6], N. Madsen[4], D. Miranda[5], P. Nolan[3], K. Ochanski[7], A.Olin[7], R.D. Page[3], L.G.C. Posada[8], F. Robicheaux[9], E. Sarid[10], H.H. Telle[6], J.-L. Vay[2], J. Wurtele[1,2], D.P. van der Werf[6] and Y. Yamazaki[11].

1 Physics Department, University of California at Berkeley, Berkeley, California 94720-7300, USA.
2 Lawrence Berkeley National Laboratory, Berkeley, California 947200-7300, USA.
3 Department of Physics, University of Liverpool , Liverpool L69 7ZE, United Kingdom.
4 Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark.
5 Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, Brazil.
6 Department of Physics, University of Wales Swansea, Swansea SA2 8PP, United Kingdom.
7 TRIUMF, Vancouver, BC, V6T 2A3,Canada.
8 Department of Physics, University of Tokyo, Tokyo 113-0033, Japan.
9 Auburn University, Auburn, Alabama 36849-5311, USA.
10Physics Department, NRCN, P.O. Box 9001, Beer-Sheva 84190, Israel.
11 Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan.

Abstract. The ALPHA experiment aims to trap antihydrogen as the next crucial step towards a precise CPT test, by a spectroscopic comparison of antihydrogen with hydrogen. The experiment will retain the salient techniques developed by the ATHENA collaboration during the previous phase of antihydrogen experiments at the antiproton decelerator (AD) at CERN. The collaboration has identified the key problems in adding a neutral antiatom trap to the previously developed experimental configuration. The solutions identified by ALPHA are described in this paper.

Keywords: Neutral atom trapping, CPT tests, antihydrogen, antiatoms.
PACS: 11.30.Er, 52.25.Fi, 39.10.+j.

INTRODUCTION

The first demonstration of antihydrogen formation was achieved by the ATHENA collaboration in 2002[1] and was subsequently confirmed by the ATRAP collaboration[2]. In the following two years routine antihydrogen production facilitated experimental studies by both groups of the characteristics of the synthesized antihydrogen[3,4,5,6,7], and a second method of producing antihydrogen was developed by ATRAP[8].

CP796 Low Energy Antiproton Physics-LEAP '05
edited by Dieter Grzonka, Rafał Czyżykiewicz, Walter Oelert, Tomasz Rożek, and Peter Winter

The original goal of both experiments was to make a precise test of CPT symmetry by making a spectroscopic comparison of antihydrogen with hydrogen. This method exploits the very high accuracy already gained in hydrogen spectroscopy[9] and remains the focus of this new effort. The ALPHA collaboration, which includes many former ATHENA members, has identified trapping as the next crucial step on the way to making a CPT symmetry test. The CERN research board has recently approved this undertaking.

The ATHENA experiment had several unique experimental strengths. The detector was capable of identifying when and where the antihydrogen annihilated in the apparatus. The geometry of the apparatus, which is open at one end, permitted the use of the highest intensity positron source[10] presently available and greatly facilitates the introduction of lasers with minimum disruption. ALPHA will build an entirely new apparatus, which retains these advantages while adding the magnetic fields suitable for trapping antihydrogen.

MAKING THE ATOM TRAP

Atom traps work by interaction of an externally applied magnetic field gradient and the magnetic moment of the atom. The trapping potential is the product of the field magnitude and the magnetic moment of the atom. For a field difference of 1 T, the well depth is about 0.7 K. High magnetic fields are required to maximize the number of trapped antihydrogen atoms. Normally conducting magnets are precluded because of space and cooling constraints.

In the Ioffe-Pritchard configuration the field in the transverse plane must be a multipole of order two (quadrupole) or more. Axial confinement is effected by means of mirror coils. It is not clear that such a field configuration is possible with permanent magnets, and a solution involving both a permanent magnet and an electromagnet is unduly involved. ALPHA has thus opted for superconducting magnets.

When superposing such fields on the existing solenoidal field of a Penning trap two challenges arise. The first is that the stability of the charged particles in the existing Penning trap may be compromised. The second challenge to the addition of the multipole is technical in nature and will be dealt with in the section on magnet construction.

Plasma Stability and The Choice Of Multipole Order

The addition of multipole fields to the solenoid means that the cylindrical symmetry of the Penning trap is lost. Field lines in the trapping region are no longer parallel to the trap axis. This is thought to have two effects. Whatever radial transport already existed in the Penning trap is exacerbated, and particles making long axial excursions simply follow the field lines to the walls. In the case of a quadrupole field these effects are at a maximum because the transverse field strength increases linearly from the axis. For the same maximum field as a quadrupole at the trap walls, higher-order multipoles have lower fields close to the axis. This is illustrated in the graph on the right in fig.1.

Some previous work has suggested that there may be stable orbits for single particles in a combined solenoidal-quadrupole field configuration[11]. Plasmas with densities from 10^6-10^8 cm^{-3} and particle numbers from 10^4 antiprotons to 10^8 electrons or positrons are far from the single particle regime. Other work[12] identified the problems associated with quadrupoles for trapped plasmas and has suggested that higher-order multipoles would largely avoid these problems.

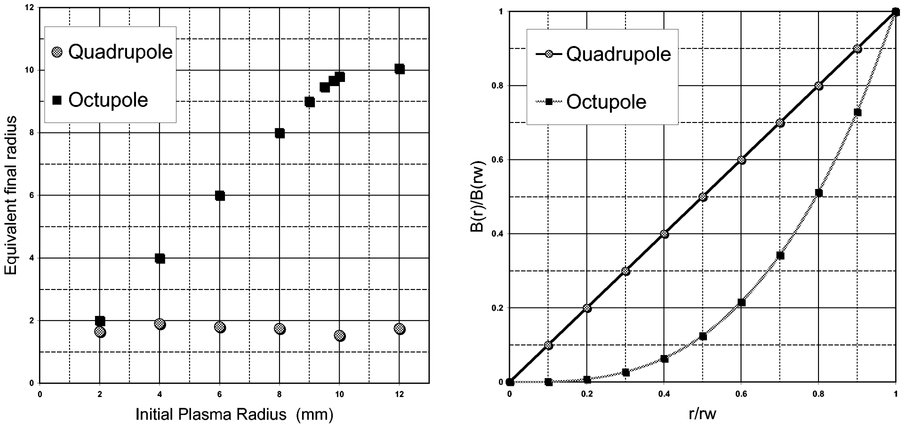

Figure 1. Left. Particle in cell (PIC) simulation results. The radius of the surviving plasma is plotted versus the initial radius. Plasmas of different radii were "loaded" and the evolution followed whilst ramping the respective multipole. For the quadrupole field particles at a radius greater than 2 mm are lost, while the octupole field allows particle survival up to 10 mm. **Right.** The amplitude of each type of field is shown as a function of radius. This is shown for illustration only.

Particle in cell simulations[13] (PIC), using the WARP program, have studied the behaviour of plasmas in both quadrupole and octupole fields. The results of the simulations are presented in fig.1 and show that the quadrupole causes strong loss in the plasma. The simulations involve the loading of electrons over 0.1 microseconds followed by the fast ramping of the multipole. The total time of the simulations is 3 microseconds but most particle loss occurs within 1 microsecond. The loss is thought to be ballistic where the particles follow the field lines to the wall. Experiments[14] were also performed with electrons in a Penning trap. Here the maximum field strength of the superposed quadrupole was of similar field strength to the solenoid. A similar ballistic loss was observed in these experiments with electrons.

A different type of experiment was performed by loading the electrons with the quadrupole off and then ramping it on. When the ramp was over the axial electrostatic trap was expanded for various times and quadrupole field strengths. The results are shown in fig.2. This result is important since any antihydrogen experiment involves substantial movement of all three charged species along the axis. Again the effect of the quadrupole is not encouraging. In light of these results ALPHA has decided to use a multipole of higher order than a quadrupole. The order chosen arises from technical considerations described below.

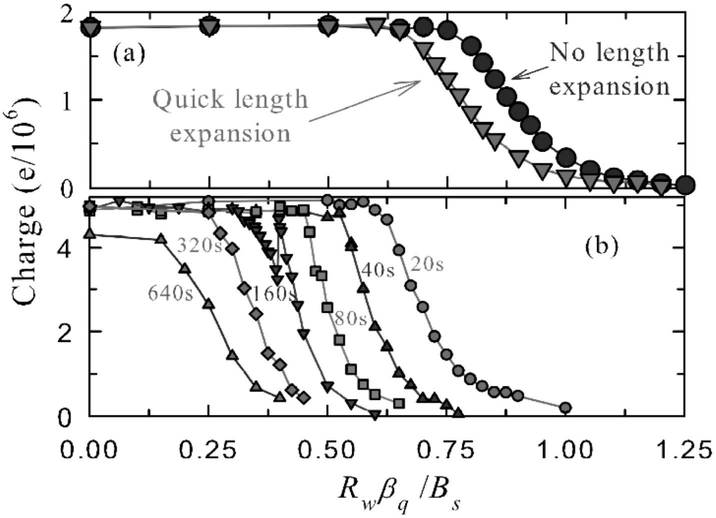

FIGURE 2. **(a)** Charge remaining in the trap as a function of the quadrupolar field. The "No length expansion" plasma was stored in a single cylinder of length 1 cm. The "Quick length expansion" plasma was briefly lengthened from 1 cm. to 4.08 cm. while the quadrupole was at full strength. (**b)** Charge remaining at the indicated times as a function of the quadrupole field. The trap length was 2 cm. The solenoidal field was 0.4 T for both (a) and (b). $R_w\beta_q$ is the field at the trap wall.

Magnet Construction

Traditional superconducting magnet techniques involve substantial metal mechanical support of the superconductor due to the forces generated. This would have a deleterious effect on the multiple scattering of pions and threaten the efficacy of our new detector. Brookhaven National Laboratory has developed a novel technique where the superconductor is laid down on a thin bed of epoxy and back filled from the top with G10 and more epoxy. A single strand of wire is applied by a computer-controlled head in a continuous manner one layer at a time.

The result is a compact light magnet with a minimum amount of scattering material between the annihilation point and the detector. A further advantage is that the innermost wire where the field is at a maximum can be laid directly on the vacuum chamber containing the trap electrodes. This utilises the precious field strength to the full and ensures an electrode temperature of 4.2 K. This is a considerable improvement over the ATHENA set up as the final temperature of the charged particles will be lower and the vacuum performance will be better. The process allows almost any coil configuration that can be drawn to be made within the mechanical limit of the bending radius of the wire. The choice of wire in also constrained by another consideration

When the multipole is immersed in a solenoid the transverse trap depth is given by

$$\Delta B = \sqrt{B_s^2 + B_{(rw)}^2} - B_s \tag{1}$$

where B_s is the field of the solenoid and $B_{(rw)}$ is the field of the multipole at the trap wall. The solenoid field is the minimum in B and to have any useful depth the multipole field should be of the same order as the solenoid field i.e. a few tesla. The presence of the solenoidal field also constrains the maximum safe multipole current above which quenches may occur.

ALPHA has made an extensive survey of many possible coil geometries including mirror coils and multipole order. We have used the known data of many of types of superconducting wire, and, where they did not exist, made measurements to characterize these. We optimized for field strength (peak current), quench safety and compatibility with the fabrication process (bending radius). We have also taken into consideration the axial trap configurations and manipulations required to get the charged species to the point of mixing.

As a result we have built a prototype octupole magnet including mirror coils. This has been added to a Penning trap and is being used for experiments with electrons. The results of this exercise will inform the decision on the final configuration.

The multipole will be immersed in a liquid helium vessel, which will in turn be contained in an evacuated vessel with suitable heat screens. The outer wall will thus be at room temperature. Similar containment of Brookhaven made magnets has been constructed previously with success.

DETECTOR DESIGN

The ATHENA detector design included two layers of silicon sensors for pion tracking detection of antiprotons and a layer of CsI crystals with diode readout for gamma ray detection of positron annihilation. The simultaneous detection of both was the basis for ATHENA's demonstration of antihydrogen detection ref.[1].

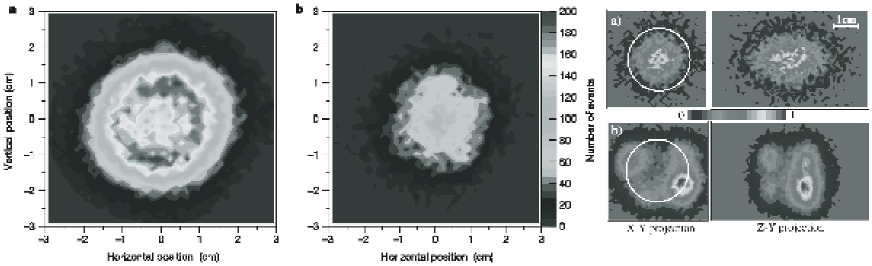

FIGURE 3. **Left.** Annihilation signal of antiprotons mixed with a) cold positrons and b) hot positrons . a) The ring pattern is consistent with neutral antihydrogen drifting out of the trap and annihilating on the wall. b) The confinement of the annihilation pattern to the centre of the trap is due to the reduction of antihydrogen formation and the annihilation of antiprotons on residual gas. **Right.** Annihilation signal of antiprotons in the trap with no positrons present. a) Here the antiprotons annihilate at the centre of the trap. b) Characteristic antiproton annihilation in "hotspots" on the trap wall.

In that article it was also shown that the detector could distinguish between annihilation at the centre of the trap and annihilation at the wall (fig.3 left). Furthermore during 2002 and subsequent years it was discovered that lone antiproton loss leads to a characteristic "hotspot" annihilation pattern at the trap wall[15] as shown in fig. 3 right. Thus with adequate resolution an unambiguous antihydrogen annihilation signal can be observed using silicon alone.

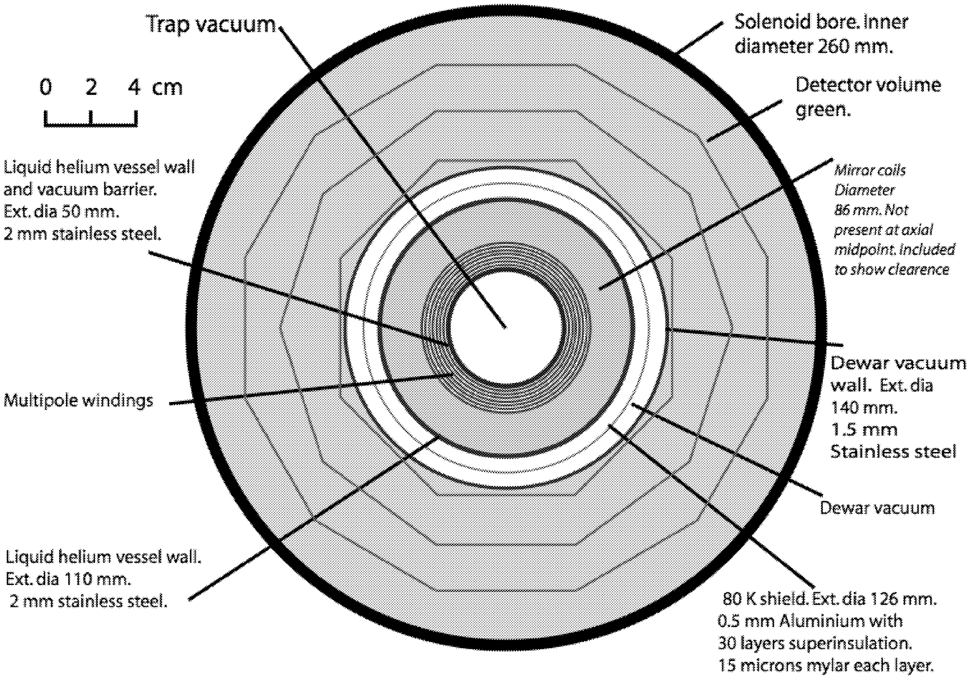

FIGURE 4. Cross-section of the apparatus in the mixing region.

An extensive Monte Carlo study, including a helix fitting routine, of a three-layered silicon detector was carried out in order to determine whether radial resolution in the new apparatus could match that of ATHENA. The pitch of the silicon strips was an important parameter in this study. The results shown below are very favourable. The resolution of the ATHENA detector was 4 mm. The ALPHA detector will use the geometry shown in fig. 4 and will not use gamma detection.

Although the new magnet design minimizes scattering material, the efficiency of gamma detection would be very low. A gamma detector would take up space that could be better used to add a third layer of silicon. This would allow the helical trajectories of charged pions to be reconstructed and thus enhance resolution. This was not possible with the two layers of silicon available in ATHENA.

The multipole Dewar and detector cannot be accommodated in the old ATHENA magnet, which had a bore of 140 mm. A new magnet with a warm 260 mm bore has been obtained, and installed in the ALPHA experimental zone. It has been energized to 3 T and a field map has been made. The warm bore and magnet Dewar have the combined advantage that the new detector can run at room temperature, which will make it more robust than the ATHENA detector which operated at 140 K. The geometry of all of the essential elements is shown in cross-section in fig. 4. It was decided to extend the trap radius from 12.5 mm to somewhere between 21-24 mm in order to enhance the resolution of the detector and to accommodate solenoid magnet operation below 3 T if this should prove necessary.

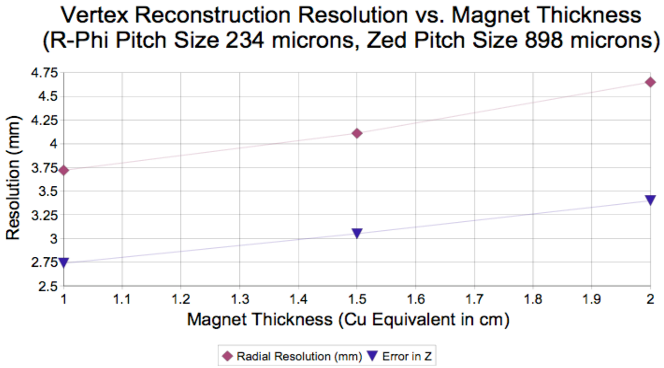

FIGURE 5. Results of the Monte Carlo simulation using the geometry shown in fig. 4 whilst varying the thickness of scattering material.

CONCLUSION

The ALPHA collaboration will continue work at the AD toward a spectroscopic comparison of hydrogen and antihydrogen and as the next step an antihydrogen trapping experiment will be attempted. Essential elements of ATHENA have been retained and the apparatus and techniques required to implement a neutral trap have been identified by experiment and simulation. The effects of adding this neutral trap to the existing Penning trap design and the detector have been studied and these have been tailored so that equivalent performance can be expected. We expect to have the complete apparatus ready in time for AD start up in 2006.

ACKNOWLEDGMENTS

We are very grateful to Prof. A. Rotondi and Dr. P. Genoa for their Monte Carlo simulations of the response of the new detector configuration in the new apparatus.

This work was supported in part by MEXT and RIKEN (Japan), NSERC and NRC (Canada), CNPq (Brazil), SNF (Denmark), and EPSRC (U.K.). The submitted manuscript has been authored by contractors of the U.S. Government under contracts No. DE-AC02-05CH11231 and W-7405-ENG-48, by the US DOE, Office of High Energy Physics, and by the National Science Foundation. Accordingly, the U.S. Government retains a nonexclusive royalty-free license to publish or reproduce the publication form of this contribution, or allow others to do so, for U.S. Government purposes.

REFERENCES

1. M.Amoretti *et al.*, *Nature* **419**, 456 (2002).
2. G. Gabrielse *et al.*, *Phys. Rev. Lett* **89**, 213401 (2002).
3. G. Gabrielse *et al.*, *Phys. Rev. Lett* **89**, 233401 (2002).
4. N. Madsen *et al., Phys. Rev. Lett* **94**, 033403 (2005).
5. M.Amoretti *et al., Phys. Lett. B* **583**, 59-67 (2004).
6. M.Amoretti *et al.*, *Phys. Lett. B* **578**, 23-32 (2004).
7. M. Amoretti *et al., Phys. Lett. B* **590**, 133-142 (2004).
8. C.H. Storry *et al*., *Phys. Rev. Lett.* **93**, 263401 (2004).
9. M. Niering *et al*., *Phys. Rev. Lett.* **84**, 5496–5499 (2000), C.L.Cesar *et al*., *Phys. Rev. Lett.* **77**, 255, (1996).
10. L. V. Jørgensen *et al., Phys. Rev. Lett* **95**, 025002 (2005).
11. T. M. Squires *et al*., *Phys. Rev. Lett.* **86**, 5266 (2001).
12. E.Gilson and J.Fajans, *Phys. Rev. Lett.* **90**, 015001(2003), J.Fajans and A. Schmidt, *NIM A* **521**, 318 (2004).
13. K.Gomberoff *et al. Private communication*. Abstract submitted. Log Number DPP05-2005-000432.
14. J.Fajans *et al*., *Phys. Rev. Lett.,* Accepted for publication.
15. M.C.Fujiwara *et al.*, *Phys. Rev. Lett* **92**, 065005 (2004).