In 2005, the Division of Nuclear Physics (DNP) created a PhD Thesis Prize competition for best thesis in Experimental or Theoretical Nuclear Physics by any student receiving their PhD degree from a Canadian University in the current or prior calendar year (see http://www.phys.uregina.ca/dnp/prize). DNP is pleased to announce that the recipient of the 2010-11 DNP Thesis Prize is Richard Hydomako. Dr. Hydomako was awarded his PhD by the University of Calgary in November 2011 for the work "Detection of Trapped Antihydrogen". A summary of Dr. Hydomako's thesis work appears below.

DETECTION OF TRAPPED ANTIHYDROGEN IN ALPHA

BY RICHARD HYDOMAKO

SUMMARY

This article describes the ALPHA silicon detector and how it was used to demonstrate the first magnetic confinement of antihydrogen atoms.

Antihydrogen, the bound state between an antiproton and a positron, is an ideal system for testing fundamental symmetries. Specifically, as the simplest anti-atomic system, antihydrogen can be used to directly probe CPT (charge-parity-time) symmetry between matter and antimatter. Moreover, since it is electrically neutral, measurements of the gravitational action on antihydrogen can proceed without the difficulties imposed by stray electromagnetic fields which are an inherent problem with gravitational experiments on charged antiparticles. To their benefit, studies of the properties of antihydrogen have the distinct advantage of being directly comparable with measurements of the well-studied hydrogen atom. Likewise, with enough study and control, the properties of antihydrogen might ultimately be determined with the same precision as their hydrogen counterparts.

Low-energy antihydrogen was first synthesized in 2002 by the ATHENA [1] and ATRAP [2] experiments. The ALPHA collaboration was subsequently formed in 2005 with the experimental goal of trapping antihydrogen atoms for the purpose of performing precision measurements. To this end, ALPHA has constructed a dedicated apparatus in the Antiproton Decelerator (AD) hall at the CERN facility, located just outside of Geneva, Switzerland. As depicted in Figure 1, the ALPHA apparatus combines a Penning-Malmberg trap for the confinement and manipulation of charged particles with a magnetic neutral-atom trap for the confinement of antihydrogen. Atoms in low-field seeking states with energies within the trap well depth ($< 50\ \mu\text{eV}$) will be confined in the minimum-B region of the neutral-atom trap due to the magnetic dipole interaction between the antihydrogen atom an the inhomogeneous magnetic field. The stable confinement of antihydrogen atoms is an essential step towards precision measurements, as it provides the opportunity to probe the antihydrogen atom in isolation for extended periods of time. Recently, ALPHA demonstrated the successful confinement of antihydrogen atoms [3] for times as long as 1000 seconds [4], which lead to the first observation of resonant microwave transitions in trapped antihydrogen atoms [5].

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The ALPHA apparatus includes a dedicated antihydrogen detector, consisting of three concentric layers of silicon strip detection modules. The silicon modules are sensitive to the passage of charged particles and can determine the point where the particles cross through their active volume. As such, the silicon detector is capable of detecting the charged annihilation products released when the antiproton in the antihydrogen atom comes into

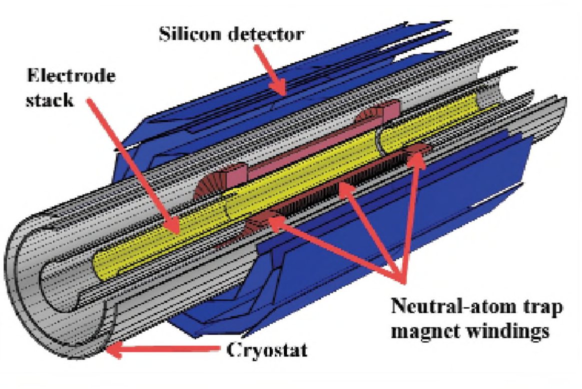

Fig. 1 Schematic diagram of the trapping region of the ALPHA apparatus. The grey cylinders show the apparatus cyrostat, the gold cylinders show the electrodes of the Penning-Malmberg trap, the magenta volumes show the location of the magnet windings for neutral-atom trap, and the blue rectangles show the positions of the silicon detector modules. This entire section of the ALPHA apparatus is located inside the bore of a solenoidal magnet (not shown), which provides the axial magnetic field for the Penning-Malmberg ion trap.

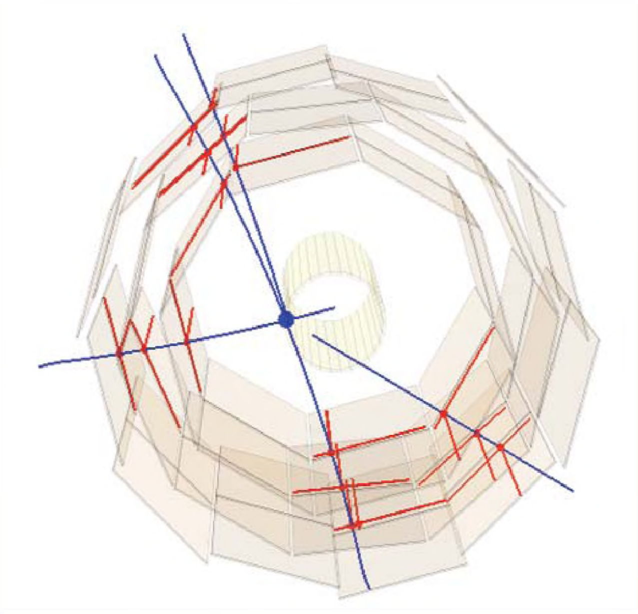

Fig. 2 Example of a 3-dimensional vertex reconstruction. The grey rectangles show the placement of the silicon detector modules, and the light yellow cylinder shows inner surface of the ALPHA apparatus (the rest of the apparatus material has been removed for clarity). The red line segments represent the silicon strips recording hits, the blue curves show the interpolated track trajectories, and the blue circle shows the determined vertex position.

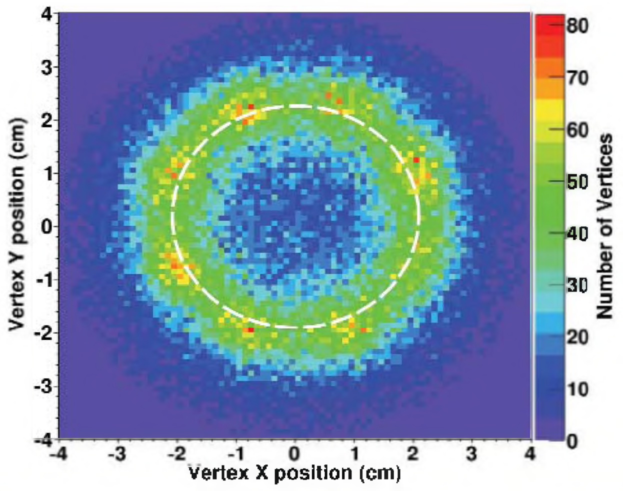

Fig 3 A transverse projection of the distribution of reconstructed vertices for unconfined antihydrogen annihilation in the magnetic field of the neutral-atom trap. The dashed white circle represents the radius of the inner surface of the apparatus.

contact with a proton or neutron. Moreover, the three layer detector configuration allows for the reconstruction of the charged particle trajectories, which can then be extrapolated back to the primary annihilation position (often called the vertex position). Figure 2 shows the reconstruction of an observed annihilation event which produced four charged particle tracks, with the blue curves depicting the extrapolated particle trajectories and the blue circle showing the determined vertex position.

The strength of the vertex reconstruction technique is apparent when many vertices are summed and the resulting distributions examined. Figure 3 shows an example transverse projection of a distribution of unconfined antihydrogen within the magnetic field of the neutral-atom trap. The ring-like shape is due the unconfined atoms annihilating on the inner wall of the apparatus. Since the charged particles must travel through several centimetres of apparatus material (including the windings of the neutral-atom trap), the reconstructed vertex positions are smeared due to multiple-scattering. This unavoidable scattering limits the vertex position resolution to about half a centimetre, which is more than acceptable for the ALPHA trap, which is about 15 centimetres in axial extent.

Because of the shallow neutral-atom trap well-depth, only very low-energy antihydrogen atoms are magnetically confined. Consequently, the detection of trapped antihydrogen amounts to a rare event search and it is critically important to have a good understanding of the detector response and the relevant backgrounds. For the ALPHA detector, the dominant background is due to cosmic-ray muons, which can leave tracks which mimic annihilation events as they pass through the detector. However, the vast majority of the cosmic-ray events can be identified and rejected using carefully placed selection criteria. These selection criteria (or 'cuts') focus on aspects of the event reconstruction where the annihilation and cosmic-ray events strongly differ, such as in the number of observed tracks and the location of the reconstructed vertex. To avoid introducing unintentional experimenter biases, a blinded analysis procedure was used when determining the placement of the selection cuts. This analysis used proxy signal and background datasets to ensure that the selection criteria were not over-fit to the specific case of the trapping experiment data. Unconfined antihydrogen annihilation events comprised the signal dataset, while the background dataset used cosmic-ray events collected while no antiparticles are present in the apparatus. After optimization, the selection cuts reject (99.54 ± 0.02)% of the cosmic-ray background set, while retaining (64.4 ± 0.1)% of the annihilation signal[6]. This results in a false-acceptance rate of $(47 \pm 2) \times 10^{-3}$ events/s, which is more than adequate to perform sensitive antihydrogen trapping experiments.

In addition to cosmic-ray muons, another possible background for the ALPHA detector are annihilations from mirror-confined antiprotons. Because of the adiabatic conservation of their magnetic moments, antiprotons with large transverse momenta can be confined (or 'mirror-trapped') in the inhomogeneous magnetic field of the neutral-atom trap. This background is particularly worrisome as a mirror-trapped antiproton annihilation has the same signature in the silicon detector as an antihydrogen annihilation. Although an electric field is pulsed across the trap axis in an effort to push the mirror-confined antiprotons out of the trap, it is difficult to ensure that all of the charged particles are removed in this procedure. To control for any remaining mirror-confined antiprotons, a reversible static electric bias field, similar to the previous pulsed field, is established during the detection window when the magnetic field of the neutral-atom trap is disengaged. Any remaining mirror-confined antiprotons will then be deflected in the direction of the bias field, with the neutral antihydrogen atoms will be unaffected. The reconstructed vertex positions can then be used to distinguish between events due to mirror-confined antiprotons, and those due to trapped antihydrogen [7]. As expected, the number of observed events attributable to mirror-confined antiprotons was found to be very low and the vast majority of events were found to be consistent with trapped antihydrogen.

In summary, the silicon detector and vertex reconstruction methods were an important part of the ALPHA experiment and were a crucial element in the demonstration of the magnetic trapping of antihydrogen. Indeed, for antihydrogen trapping experiments described in Ref. [3] the silicon detector recorded over six hundred events in total, which, using the selection criteria described above, was ultimately reduced to a set of 38 annihilation events consistent with the release of trapped antihydrogen. Furthermore, this detector, and these techniques, will continue to be employed as part of future spectroscopic measurements in ALPHA. As such, these methods will prove invaluable in the on-going comparison between hydrogen and antihydrogen.

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