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The ALPHA antihydrogen trapping apparatus

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ABSTRACT

The ALPHA collaboration, based at CERN, has recently succeeded in confining cold antihydrogen atoms in a magnetic minimum neutral atom trap and has performed the first study of a resonant transition of the anti-atoms. The ALPHA apparatus will be described herein, with emphasis on the structural aspects, diagnostic methods and techniques that have enabled antihydrogen trapping and experimentation to be achieved.

1. Introduction

Trapping antihydrogen ($\overline{\mathrm{H}}$) atoms is an important milestone towards the goal of precision spectroscopic comparisons of the

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properties of antihydrogen and hydrogen. Such comparisons will allow direct tests of the CPT theorem, according to which no difference is expected between the energy levels of the atom and its antimatter counterpart. The ALPHA collaboration has recently trapped antihydrogen atoms. In the first report [1], 38 atoms were trapped for 0.17 s, soon followed by much longer (1000 s) confinement times [2] of a larger trapping sample. Atoms trapped for such long times are expected to only occupy their ground state [2]. Recently, ALPHA demonstrated the first resonant microwave interactions probing the hyperfine structure of the antihydrogen ground state [3]. It is anticipated that the most precise measurement of the energy levels of the antihydrogen atom will be achieved via two-photon excitation from the 1S to the 2S level. A comparable measurement with normal hydrogen atoms enabled the frequency of this transition to be determined with a relative precision of better than 10^{-14} [4].

The ALPHA experiment uses antiprotons ($\bar{p}$) supplied by the CERN Antiproton Decelerator (AD), a unique facility that provides bunches of the antiparticles at relatively low energy (5.3 MeV) [5]. Following further energy degradation, by about three orders of magnitude, a fraction of these antiprotons are stored in a charged-particle trap. Positrons (e^+) are routinely obtained from a ^{22}Na source, and a near-monoenergetic low energy beam can be formed to facilitate their capture using well-established techniques. ALPHA uses Penning-Malmberg [6] traps to separately confine the antiprotons and positrons. Only after these charged particles are manipulated and cooled, are they mixed to produce antihydrogen atoms.

The ALPHA experiment is the successor to the ATHENA experiment, which produced the first cold antihydrogen atoms in 2002 [7]. The ATHENA traps, however, were only for charged particles, and no means were provided to confine the neutral antihydrogen atoms. As a consequence, these anti-atoms escaped to annihilate on the wall of the trap shortly after they were formed. The main new feature introduced by ALPHA is an inhomogeneous magnetic field that can hold neutral atoms using the interaction of the magnetic field with the magnetic dipole moment of the atoms. This trap uses an octupole magnet to provide the radial confinement of the antihydrogen, and mirror magnets to provide the axial confinement (see Section 2.6).

Because the magnetic potential well is shallow for ground state atoms, only those that are very cold (kinetic energy equivalent to less than around 0.5 K) can be trapped. Thus, the antihydrogen must be produced from antiparticles cooled as far as possible in order to enhance the capture probability. Cooling is also important to enhance the production of the antihydrogen atoms, since the main production mechanism is considered to be three-body recombination (i.e. $\overline{p}+e^{+}+e^{+}\rightarrow\overline{H}+e^{+}$) which depends very strongly on the positron temperature (see e.g. [8]).

The fundamental cooling mechanism employed in ALPHA is the emission of cyclotron radiation of the charged particles gyrating in the magnetic field. Because of their low mass, positrons can cool directly, in principle equilibrating with the cryogenic walls of the trap. The heavier antiprotons are confined together with electrons, and transfer kinetic energy to them through collisions. The electrons, in the same way as the positrons, radiate this energy away. In practice, we find that both the positrons and the antiprotons are hotter than the temperature of the wall of the trap, which is measured to be 8 K. We employed additional cooling techniques, such as evaporative cooling (see Section 4.3.1) in order to further cool the species.

In the first trapping experiments, trapping was demonstrated by allowing the anti-atoms to escape after turning the confining magnetic fields off. The anti-atoms could then hit the walls of the trap where they annihilated. Our main diagnostic device for the annihilation products (mainly pions from antiproton annihilations) was a 60-module silicon detector that surrounded both the trap electrodes and the magnetic trap, as shown schematically in Fig. 1. This detector is described more fully in Section 3.1. A major effort was necessary to unambiguously identify the annihilation events as being caused by antihydrogen atoms by establishing their charge neutrality (to rule out trapped antiprotons) and to carefully distinguish them from cosmic rays events [1,9].

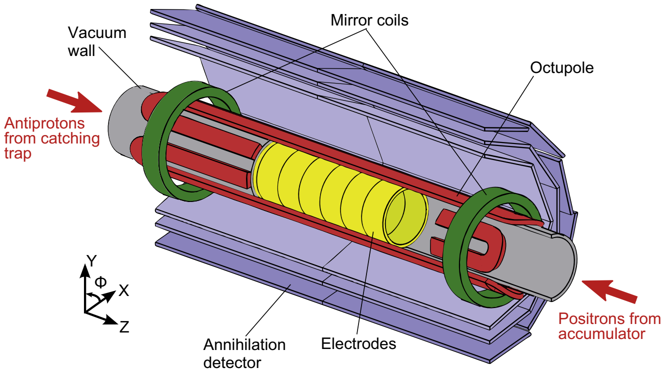

Fig. 1. Schematic illustration of the inner section of the ALPHA experiment showing the Penning-Malmberg trap electrodes, the neutral trap (comprising the octupole and mirror coils) and the silicon-based annihilation detector. The components are not drawn to scale.

The success of the antihydrogen trapping endeavour was based on many innovations in methods of handling the antiprotons and positrons in order to mix them with the maximum spatial overlap, while keeping them as cold as possible. Amongst the techniques used to manipulate the charged particle plasmas, and to be described below (Section 4), were 'rotating walls' to control the size of the plasmas, and autoresonance excitation to enable the mixing of the antiprotons and the positrons without excessive heating.

The general structure of the paper is as follows. Section 2 contains a general description of the layout and vacuum and cryogenic infrastructure of ALPHA, together with details of the charged particle traps, the positron accumulator and magnetic minimum neutral atom trap. Section 3 comprises a summary of the detection systems used in the experiment, whilst Section 4 describes methods and processes, including details of charged particle manipulations, as well as the monitoring systems developed by ALPHA.

2. Apparatus structure, vacuum and cryogenics

2.1. Overview

The ALPHA experiment resembles, in several aspects, its predecessor, the ATHENA apparatus, which was used to produce antihydrogen from cold trapped plasmas in 2002 [7]. It features an open geometry, which allows particle insertion into the cold portion of the apparatus from the room temperature region (electrons) and also from adjacent machines (positrons and antiprotons). This geometry also allows easy particle extraction for the plasma diagnostic techniques available in the warm region (radial profile imaging and temperature measurement) and the introduction of microwave radiation into the trap [3].

From a functional point of view, the experimental system must produce a strong solenoidal magnetic field for stable charged-particle confinement in Penning-Malmberg traps and to supply the high gradient magnetic fields required for (neutral) antihydrogen trapping. In addition, it should also provide a cryogenic