The ATHENA experiment for the study of antihydrogen

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In 2002, the ATHENA experiment was the first to produce large amounts of antihydrogen atoms at the CERN Antiproton Decelerator (AD). In this review article, we collect and discuss all the relevant results of the experiment: antiproton and positron cooling and their recombination dynamics in the nested Penning trap, the methods used to unambiguously identify the antiatoms as well as the protonium background, the dependence of the antihydrogen formation on mixing time and temperature. An attempt to interpret the results in terms of the two-body and three-body formation reactions, taking into account the complicated nested-trap dynamics, is also made. The relevance of the ATHENA results on future experiments is discussed, together with a short overview of the current antimatter physics at the AD.

Keywords: Antihydrogen atom formation; nested Penning traps; annihilation detectors.

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1. Introduction

The ApparaTus for High precision Experiments with Neutral Antimatter (ATHENA) experiment takes an important place along the path that, starting from the discoveries of the positron ($e^+$) and antiproton ($\bar{p}$), opens the way to the study of complex atomic systems made of antimatter with atomic physics techniques. ATHENA was the first experiment, in 2002, which demonstrated that a large amount of cold antihydrogen ($\bar{H}$) can be obtained by mixing $e^+$ and $\bar{p}$ in a nested Penning trap, after cooling the two species.\(^1\) The parameter dependence of $\bar{H}$ formation has been extensively studied by ATHENA. These results have determined the boundary conditions for the design of many of the successor experiments devoted to produce and manipulate cold antihydrogen.

By allowing to fully monitor the annihilation of single antiatoms, the ATHENA detectors (see Sec. 3) afforded a complete picture of the $e^+$ and $\bar{p}$ dynamics in the mixing trap and the ATHENA diagnostics procedures also helped control and progressively improve the $e^+$ and $\bar{p}$ cooling and manipulation (see Secs. 4–7).

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This work provided quantitative information on many aspects of the formation processes, that are discussed in Sec. 8. Much of this information is useful also for atomic physics experiments with ordinary matter, because in this case the absence of the annihilation makes it difficult to analyze events at the level of single atoms.

Thanks to its advanced detection capabilities, ATHENA was also able to detect and characterize the non-H events present as a background in the central part of the mixing trap. These events have been identified as the annihilations of the protonium (pp) bound state, formed by the interaction of cold \( \bar{p} \) with a trapped cloud of molecular hydrogen ions. The interesting properties of this system are described in detail in Sec. 9.

After the detailed illustration and discussion of the aforementioned topics, we conclude by discussing the ATHENA results in the light of current and future antimatter experiments in Sec. 10.

Before proceeding to discuss these topics, in the next section we would recall briefly some aspects of the antimatter physics that are of relevance for the following.

2. Atomic Physics with Antimatter

The concept of antimatter first arose in the context of Paul Dirac’s equation describing the properties of particles with half-integer spin, such as the electron.\(^2\) Dirac himself realized soon afterward that the equation had a corresponding negative energy solution for every ordinary positive solution. After initially dismissing them as unphysical, he later interpreted these negative solutions as representing the antimatter counterparts to ordinary particles.\(^3\) Galvanized by this prediction, experimentalists began looking for the unique signatures of antiparticles in the naturally occurring cosmic radiation.

Less than two years later, the antielectron, dubbed the positron, was discovered and unambiguously identified in cloud chamber photographs.\(^4\) With the successful discovery of the antiparticles of the proton and the neutron during the 1950s at the Bevatron accelerator at Berkeley,\(^5,6\) the possibility that all elementary particles had an antimatter counterpart was being seriously considered. It was formally expressed as the \( CPT \) theorem by Pauli, who postulated that all physical laws continue to hold when the combined \( CPT \) operator — charge conjugation, parity, and time reversal — is applied to any system.

2.1. \( CPT \) symmetry

It follows from the \( CPT \) theorem that any particle is transformed into its antiparticle when the \( CPT \) operations are applied to its wave function, and that furthermore the particle and antiparticle have identical properties, such as lifetime, inertial mass, but their internal quantum numbers, like electric charge and magnetic moment, are opposite. The collision of a particle with its antiparticle leads to the annihilation of both and the release of the same amount of energy in the form of photons or lighter particles.
In the framework of modern quantum field theories, \( CPT \) symmetry arises automatically as long as the theories meet certain fundamental requirements, such as a flat space–time structure, the Lorentz invariance and the pointlike nature of elementary particles. However, at very small length scales, some theories introduce additional spatial dimensions or a preferred direction in the vacuum which is frozen and extends over all space and time,\(^8\) thus opening the possibility for \( CPT \) violations, which would express themselves as minute deviations between the properties of matter and antimatter particles.

According to our current understanding of the formation of the universe, equal amounts of matter and antimatter were created in the big bang approximately 13.8 billion years ago. Surprisingly, all celestial objects observable today, such as galaxies and individual stars, are made of ordinary matter. If they were not, the nucleosynthesis process in stars, by which the heavier elements are formed, would invariably lead to the emission of such antiatoms, some of which should also arrive at earth.

In 1998 the AMS-01 experiment was conducted on board the space shuttle Discovery. It orbited Earth for 10 days at an altitude of 400 km and registered the signals of heavy atomic nuclei. In the course of that experiment, several million helium nuclei were detected, but not a single antihelium nucleus.\(^9\) This experiment provides the current limit for the fraction of antibaryons to baryons in the universe. It could be explained by a minute violation of the discrete symmetries which relate matter to antimatter, or by an anomalous gravitational interaction between them.

Just over 50 years ago, it was assumed that the parity and charge-parity symmetries also held separately, but \( P \) and \( CP \) violations have since been discovered in nuclear beta decay and the decay of neutral kaons, respectively.\(^{10,11}\) The experimentally established \( CP \) violation, however, is too weak to explain the observed baryon asymmetry according to the Sakharov conditions. Consequently, \( CPT \) symmetry has been tested very thoroughly by comparing many different properties of a variety of antimatter–matter particle pairs. For instance, the mass-to-charge ratios of the \( e^-/e^+ \) and \( p/\bar{p} \) pairs have been compared to high precision in Penning traps.\(^{12,13}\) None of these or any other \( CPT \) tests performed to this day have revealed a deviation from the exact \( CPT \) symmetry. Hence, the \( CPT \) theorem remains an integral part of the Standard Model. It must be emphasized, however, that the absence of a deviation in one characteristic of a particle–antiparticle pair, such as the mass, does not rule out differences in other properties. Therefore, further high precision comparisons of particles and their antiparticle counterparts continue to garner significant interest, especially if they hold the prospect of improving upon the experimental precision of earlier studies.

In this context, the frequency of the atomic \( 1S - 2S \) transition in antihydrogen is a promising candidate. The metastable \( 2S \) state, with a comparatively long lifetime of 122 ms and the correspondingly narrow natural line width, is particularly suited for high precision measurements. Using the well-established method of two-photon spectroscopy, this transition in hydrogen has been determined with a relative
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The precision of $4 \times 10^{-15}$, making the Rydberg constant, which is derived from this transition frequency, the most precisely determined of all fundamental constants. For obvious reasons, it would be desirable to perform the same experiment on antihydrogen atoms, provided they can be created, cooled and stored in the laboratory in sufficient numbers.

2.2. Antimatter gravity

The apparent disappearance of antimatter could be due to segregation in remote regions of the universe. A possible explanation of this effect relies on an anomalous behavior with respect to the gravitational force. Gravity has until now resisted all efforts to combine it with the other forces into a “theory of everything.” Notwithstanding the fundamental obstacles, quantum theories of gravity are being developed, in which the interaction is mediated by hypothetical exchange particles, the so-called gravitons. They can be repulsive or attractive, depending on the spins of these exchange bosons as well as the signs of the mass “charges” to which they couple. Hence, the formulation of a quantum theory of gravitation automatically brings about the possibility of different types of exchange particles as well as negative mass charge. Efforts to formulate a renormalizable quantum field theory of gravitation have so far been unsuccessful, but may prove feasible within the framework of an effective field theory (see for example Ref. 15).

Within such a theory, the infinite range, attractive ordinary “Newtonian” gravity is associated with a massless tensor (spin-2) exchange particle. In addition to this tensor part, gravity could also include contributions from scalar (spin-0) and vector (spin-1) components. As a general rule, even-spin exchange particles create an attractive force between all types of charges, whereas the exchange of odd-spin particles leads to a repulsive force between like charges. Therefore, it is possible that hypothetical scalar and vector parts of gravity cancel out when applied to ordinary matter, but they would produce some effects when studying the interaction between ordinary matter and antimatter. Such a deviating behavior of antimatter in the earth’s gravitational field, for instance, would therefore constitute a violation of the weak equivalence principle (also called the universality of free fall) and thus directly contradict the general theory of relativity.

Many arguments against “antigravity,” i.e. a tensor-type gravitational interaction with opposite sign for antimatter, have been put forward. All of these arguments, however, do not apply to more elaborate models involving scalar and vector gravitons. While the behavior of ordinary matter under the influence of gravity has been thoroughly tested over a large range of distance scales, the same is not true for antimatter. In fact, no experimental study on the behavior of antimatter particles in a gravitational field has ever been successfully carried out. Previous attempts to measure the gravitational acceleration of $e^+$ and $\bar{p}$ were foiled by the overwhelming effect of stray electric and magnetic fields on the electrically charged test particles.
Evidently, neutral $\bar{H}$ can overcome this fundamental limitation of charged elementary antiparticles. A first direct observation of the gravitational interaction between matter and antimatter has therefore come within reach.

2.3. Towards antiatom physics

Almost twenty years ago, physicists working on the PS201 experiment located at the Low Energy Antiproton Ring (LEAR) at CERN first managed to synthesize eleven atoms of antihydrogen ($\bar{H}$) from high energy $\bar{p}$ beams. The Fermilab E862 experiment later reported the detection of 57 $\bar{H}$ atoms, produced with a similar technique. The antiatoms produced by the LEAR experiment were formed by $\bar{p}$ at a momentum of 1.94 GeV/c traversing a Xe cluster target. At these experimental conditions, the $\bar{H}$ production cross-section was expected to be around 6 nb. A good $\bar{H}$ event consisted of a coincidence between the $\bar{p}$ and $e^+$ signals, in correspondence of some time, energy, and directional cuts.

The neutral $\bar{H}$ atoms, once formed, were no longer confined by the magnetic fields of the storage ring, and escaped toward the detectors through a gap in one of the dipole magnets. However, the high energy of the produced $\bar{H}$, together with the low number of detected events, prevented any further investigation. To overcome these difficulties the TRAP collaboration at LEAR explored an alternative way to the production of antihydrogen that proceeded through the merging of two trapped and cold antiparticle plasmas. This technique was successfully demonstrated by the TRAP collaboration with the capture and cooling of antiprotons in a cylindrical Penning trap.

After these experiments, it was quite natural to explore the possibility to form $\bar{H}$ atoms at low temperature, with a view to confining them in a trap for atomic physics studies. This second generation of experiments was initiated in 1999 at LEAR’s successor, the Antiproton Decelerator (AD) at CERN. In 2002, the ATHENA collaboration first succeeded in reaching this important milestone on the way to the main goal of $\bar{H}$ physics. The first cold $\bar{H}$ was obtained by mixing antiprotons with a dense cold positron plasma in a Penning trap. The formation of $\bar{H}$ was reproduced shortly afterward at AD by the competing ATRAP group.

After this step, the quest is now to capture neutral $\bar{H}$ into a neutral-atom trap, with the goal of subsequently performing $1S-2S$ spectroscopy on the confined antiatoms and experiments on gravity. These experiments will be reviewed in Subsec. 10.2.

3. The ATHENA Experimental Apparatus

The apparatus that produced and detected for the first time cold $\bar{H}$ atoms is shown in Figs. 1 and 2. Low energy antiprotons are extracted from the CERN AD. The 5.3 MeV kinetic energy of the extracted beam is far above what a catching trap experiment requires. Therefore, in ATHENA a further deceleration is achieved through an aluminum foil
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Fig. 1. ATHENA apparatus. Figure from Ref. 27.

Fig. 2. Top view of the $\bar{p}$ beam line. The dashed rectangles show the locations of the scintillator detectors below the magnet. Figure from Ref. 27.

degraded and the silicon beam detector at the entrance of the beam. This causes the loss of most of the beam (95%) and a big loss of density. In order to increase the density, an additional Extra Low Energy Antiproton ring (ELENA) will be constructed in the AD hall. This ring, having a circumference of about 30 m, will work as a post-decelerator, decreasing the beam energy from 5.3 MeV to 100 keV. It is planned to be ready in 2017.
After the degraders, a superconducting solenoid (3 T) with a cold bore houses the antiproton capture trap and the antiproton–positron mixing trap. The antiprotons, after the moderation, are then reflected in the catching trap by a high voltage electrode. About 500–700 ns after the arrival of the pulse, a high voltage potential is raised on the entrance electrode to capture the antiproton bunch. They are then cooled inside the catching trap to meV energies by Coulomb interactions with a pre-loaded electron cloud. The antiprotons are confined in the radial direction by the magnetic field of the 3 T solenoid and in the axial direction by an electrostatic field produced by ten cylindrical electrodes having an inner diameter of 2.5 cm. The field configuration is similar to the one used in Penning traps.

The positrons from a 1.4 GBq (40 mCi) $^{22}\text{Na}$ source are moderated in solid neon and transferred into a longitudinal magnetic field region where they lose energy by collisions with nitrogen gas and are eventually confined in a system of cylindrical electrodes. They are then transferred to the superconducting solenoid where they are held in a trap similar to the one used to store the antiprotons. The particles stacked in the two traps are transported to the mixing trap held at a pressure below $10^{-12}$ mbar. The formation of antihydrogen atoms is studied by observing their annihilation when they impinge upon the electrodes of the mixing trap. The annihilation detector, a large solid angle array of silicon microstrip counters and CsI crystals, surrounds the mixing trap. It measures the charged hadron tracks (mostly pions) emitted by the annihilation of the antiproton, in temporal and spatial coincidence with the two back-to-back 511 keV photons from $e^+e^-$ annihilation.

In the following of this section the most important features of the apparatus are described in more detail. The complete description can be found in Ref. 27.

### 3.1. The magnet, the cryogenic cold nose and the vacuum system

The magnet consists of a superconducting solenoid with a 15 cm diameter room temperature bore and a homogeneous field region of 1 m length, which operates at 3 T. To allow easy access to the trap without disturbing the cryogenic system of the magnet, a separate continuous flow cryostat (cold nose) is installed in the bore of the magnet to cool the vacuum shell housing the trap. In these conditions, the electrons and positrons cool very efficiently by synchrotron radiation in the 3 T field, so that a low ambient temperature allows production of very cold positron and electron plasmas and, via sympathetic cooling, also very cold antiprotons. The cold nose is closed off at the end toward the AD beam line by the degrader foils and a silicon beam counter whereas, toward the positron accumulator, it has an open connection to a room temperature vacuum chamber. To allow radial space for mounting the trap, the trap vacuum system, the cold nose, and finally the detector, a common nitrogen shield for both the main magnet system and the cold nose was designed. Under normal operation a temperature of 130 K was achieved on the bore walls.
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Electromagnetic (e.m.) traps of the Penning and Penning–Malmberg types\(^{28}\) are used to store, cool and manipulate the charged particles required by ATHENA (positrons, antiprotons and the electrons necessary to cool the antiprotons). These traps (with the exception of the positron accumulator) are all situated within the vacuum vessel of the cryogenic cold nose inside the superconducting solenoid. The trap environmental temperature is representative of the equilibrium temperature of the antiproton and electron clouds at the end of the cooling process. Most of the walls in the room temperature section have been coated with a NEG (Nonevaporable Getter) material. The pressure can only be directly measured in the room temperature region, where \(10^{-11}\) mbar is routinely achieved. The maximum temperature of the trap is approximately 15 K with the complete apparatus installed inside the cold nose.

3.2. The beam detectors

The antiproton beam is monitored through antiproton annihilations on the degraders and on the trap walls (Fig. 2). The system consists (i) of a silicon counter which provides the \(\bar{p}\) trigger for the catching trap high voltage switch and measures the beam profile and (ii) of the external beam detectors, formed by the front and barrel plastic scintillators, which detect the annihilation in a pulse mode and monitor the beam intensity and stability.

The external beam detectors consist of fast plastic scintillator slabs modules, made from 1 cm thick Bicron BC408 plastic scintillators, ranging from \((19.5 \times 10)\) cm\(^2\) to \((80.0 \times 19.5)\) cm\(^2\), covering about 4% of the solid angle, when antiprotons annihilate on the degraders. Due to the high instantaneous rate \((\approx 10^{14}\) s\(^{-1}\)) during the \(\bar{p}\) pulse, these detectors do not count single particles, but operate in current mode, measuring the total charge deposited by the annihilation products. However, the light produced in a 1 cm thick plastic scintillator would saturate the photomultiplier. We therefore used proximity focused Hybrid Photo Diodes (HPD).\(^{29}\) The gain of a few thousand without preamplifier is enough to detect the large amount of light generated by the product of the antiproton beam annihilations. The system is calibrated in term of incoming number of antiprotons by comparing the charge measured with the silicon beam counter and the ADC signals of the HPDs coupled to the scintillators with the counts obtained by activating aluminum foils with the antiproton beam. An accuracy of about 15% has been achieved.\(^{27}\)

3.3. The trap system

The trap system is realized by a sequence of electrodes having 1.25 cm inner radius and various lengths. Proceeding from the antiproton beam entrance and moving toward the positron accumulator, the first 12 electrodes are used to catch, cool and accumulate antiprotons (catching trap). The following group of electrodes is referred to as the mixing trap, where the antiprotons are merged with the positron plasma.
and the antihydrogen atoms are formed. This is the region where the last group of electrodes of the mixing trap is used during the positron transfer and recapture procedure. The last part of the system is the positron accumulator, which is based on the buffer gas capture and cooling of positrons in a Penning–Malmberg trap.\textsuperscript{30–32}

Static or varying voltages can be applied independently to each electrode allowing the electric field inside the trap to be shaped according to the particular operation required.

Many details on the trap system are given in Ref. 27. Here we recall the main physical characteristics that are important for the following discussion on the ATHENA results.

The catching trap is a Penning–Malmberg trap in which antiprotons are trapped and then cooled by Coulomb collisions in an electron cloud. Antiprotons, together with the electrons, are subsequently transferred to the adjacent mixing region, and the electrons removed by applying fast, pulsed electric fields. As a result about 10\(^4\) antiprotons per AD bunch are available for mixing with the positrons.

The mixing trap combines the \(\bar{p}\) and \(e^+\) clouds in the so-called nested potential configuration,\textsuperscript{33} which permits simultaneous axial confinement of oppositely charged particles (Fig. 3). In the ATHENA nested trap, cold positrons are confined in the region that constitutes the central well. Note that the positron space charge effectively flattens the on-axis potential in the mixing region.\textsuperscript{34}

The third trap is the positron accumulator, which traps and cools a continuous beam of slow positrons. These are generated by moderating \(\beta^+\) particles from a 1.4 GBq (40 mCi) \(^{22}\)Na radioactive source and guiding them into the trapping region using axial magnetic field transport. A cryogenic cold head capable of reaching 5.5 K cools down the source and makes it possible to grow a solid neon moderator directly
on the source. A NaI(Tl) detector is located close to a gate valve which can be used to isolate the source/moderator end of the apparatus and the main trapping region. This facilitates optimization of moderator growth, with the closed valve used as a simple positron annihilation target.

The system is able to trap up to $2 \times 10^8$ positrons prior to transfer them across a low field region to the mixing trap. An upper limit of $1.2 \times 10^8$ positrons and a density of $2.6 \times 10^{10}$ cm$^{-3}$ have been reached. Moderation efficiencies (absolute beam intensity divided by the total positron activity of the source) of around 0.4% are routinely achieved such that beam intensities greater than $5 \times 10^6$ positrons per second are available. One of the trapping electrodes is split into six segments to compress the plasma by applying a rotating electric field (the so-called rotating wall technique). In this technique the rotating electric field transfers torque to the plasma resulting in radial compression. The plasma has a width of 15 mm Full Width at Half Maximum (FWHM) when no rotating wall is applied, reduced to 3–4 mm following compression. Since the total number of positrons stays constant, or in some cases increases, the central density increases by more than a factor of ten.

The transfer section consists of a number of transfer electrodes and a transfer magnet capable of pulsing from 0 to 1 T in 20 ms and staying at 1 T for 1 s (see Sec. 5).

3.4. The external annihilation detectors

These detectors can be used to detect single $\bar{p}$ annihilations in charged mesons on the residual gas of the traps or on the trap walls. They consist of six coincidence pairs of Bicron BC408 10 cm thick plastic scintillators readout on both sides by Philips XP2020 photomultipliers in coincidence. They cover a solid angle of $\simeq 30\%$ with slight variations depending on the exact position of annihilation inside the traps. The appropriate thresholds are determined using minimum ionizing particles, both from cosmic rays and from $\bar{p}$ annihilation. Pairwise coincidences allow operation at a lower threshold, reducing the random noise as well as suppressing neutral background from gammas and neutrons.

This system of external scintillators is a fast detector that has been used to trigger the antihydrogen detector readout and also to count the charged particles released by the traps during the dumping of the confining potentials (see Fig. 4). This was one of the methods used to study the performances of the different trapping and cooling techniques employed and their efficiency in the antihydrogen production (see Subsec. 8.1).

3.5. The mixing operations

After the cooling $\bar{p}$ are transferred by adiabatically moving the electric voltages along the traps. Although the cold antiproton storage time is greatly reduced by the presence of the electrons (see Fig. 5), it is long enough for an efficient transfer (see Sec. 4).
Fig. 4. During the dumping of the confining potential in the mixing trap the antiprotons escape and the mesons coming from their annihilation on the trap walls are detected by the external scintillators. Figures from Ref. 36.

Fig. 5. Storage time in the catching trap for cold antiprotons with (squares) and without (circles) electrons. The antiproton numbers are normalized to the beam intensity measured with the HPD-based external beam detectors. The lines are to guide the eye. Figure from Ref. 27.
After accumulation the positrons are transferred to the mixing trap inside the main 3 T magnet. The nitrogen buffer gas is pumped out and, after the pressure in the positron accumulator has fallen below $10^{-8}$ mbar, the valve is opened and a pulsed transfer magnet is energized for 1 s. This transfer magnet produces a field of 1 T and thus helps to bridge the low field region between the positron accumulator and the main ATHENA magnet (see Fig. 1) while also making it possible to separate the two vacuum systems with a pumping restriction. The positrons are released by lowering a gate electrode with a fall time of 1 $\mu$s and trapped by closing another gate electrode in the main magnet, 3.2 $\mu$s later. This traps the positrons initially in the entire length of the mixing trap and the adjacent positron trapping section. The positron plasma is then subsequently axially compressed into the central harmonic region of the mixing trap. This compression takes a few tens of seconds. The overall efficiency for transfer, recapture and compression is about 50%. It should be noted that this efficiency was found to be mainly limited by the electronics, particularly the closing time of the trapping electrode in the main magnet. This settings allows the delivery of about 75 million $e^+$ for recombination every 5 min. The lifetime of the compressed positrons in the mixing trap is quite long as no significant loss was observed during a hold period of 4000 s.

The mixing of antiprotons and positrons takes place in the central section of the mixing trap, after the kick-out of the electrons, when they are transferred together with the $\bar{\bar{p}}$. In order to simultaneously confine the oppositely charged positrons and antiprotons, the axial electrostatic potential in the recombination region is operated in a so-called nested-trap configuration. The nested trap is achieved by applying an electric potential as shown in the graph of Fig. 3. First, the central well of the trap is loaded with the positrons. Like electrons, they rapidly cool to the temperature of the surrounding trap ($\approx 15$ K) by emission of synchrotron radiation due to their high frequency ($\approx 85$ GHz) cyclotron motion in the strong magnetic field. The $10^4 \bar{\bar{p}}$ are initially transferred to a small lateral well (dashed line in the figure) before being launched, after the electron kick-out, into the $e^+$ plasma with a kinetic energy of about 10–30 eV. By Coulomb collisions with the positrons, they are cooled to the same temperature with a cooling time constant which we have experimentally determined to be $\tau_p \approx 10$ ms (see Ref. 36 and Sec. 8).

After about 20–30 ms, $\bar{\bar{H}}$ production begins spontaneously.

As soon as neutral antihydrogen atoms are formed, they are no longer confined in the charged particle trap but are ejected from the mixing region with a momentum essentially equal to that of the antiproton just prior to recombination.

### 3.6. The antihydrogen detector

In the homogeneous magnetic field of the mixing trap the electrically neutral $\bar{\bar{H}}$ atoms escape the confinement region and annihilate on the trap electrodes. In the trap material, the $\bar{\bar{p}}$ annihilation on some nucleus produces pions ($\pi$) and kaons ($k$) (on average about three charged pions), whereas the $e^+$ forms the positronium.
with an $e^-$ and the positronium annihilation produces three $\gamma$'s or two 511 keV $\gamma$'s. In dense media, the positronium collisions generate rapidly the para-positronium state that decays almost immediately, after 125 ps, by the two-$\gamma$ emission. This is the characteristic $e^+$ annihilation signal that must be detected.

Therefore, the goal of the ATHENA detector is to detect antihydrogen annihilations by the space–time coincidence of the $\bar{p}$ and $e^+$ annihilations, that is to register charged mesons and two back-to-back $\gamma$ rays in the same time window, determining if the ideal line joining the two $\gamma$ ray impact points passes through the annihilation vertex reconstructed by the charged meson tracks.

The detector, shown in Fig. 6, was designed to allow extraction of a clean $\bar{H}$ signal for background rates of up to 10 kHz, although the effective background rate was later found to lie below 100 Hz. Charged particles are detected in two layers of Si-$\mu$-strip modules covering roughly 80% of the solid angle. A three-dimensional reconstruction of the $\bar{p}$ annihilation vertex is achieved with $\sigma = 4$ mm spatial resolution by straight line extrapolations of the charged particle tracks. Photons from positron annihilation (511 keV) convert in the CsI crystals via the photoelectric effect with a probability of about 25%. The reconstruction efficiency for $\bar{He}$ events can, in principle, be increased if Compton scattering is also included. The segmentation into 192 crystals is required to ensure high enough angular resolution to verify that the two 511 keV photons are emitted back-to-back. High granularity is also imposed to suppress the high background generated by high energy $\gamma$'s from the decay of $\pi^0$'s coming from $\bar{p}$ annihilation. With 192 crystals the probability of a crystal being hit by either a pion from the annihilation vertex or one of the high energy $\gamma$'s is about 5% per crystal. This background contains (spatially uncorrelated) 511 keV photons produced by $\gamma$ showers in the surrounding apparatus (mainly the magnet.
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cobs). This background signal will always be present in our antihydrogen signal but it does not exhibit the angular correlation of 180° between the two lines joining the charged meson vertex with the centers of the two crystals hit by γ's (see Fig. 6).

The detector operates at a temperature of 140 K, determined by its location a few millimeters from the cold (15 K) trap region in the center of the experiment. The small dimensions and the low temperature put constraints on mechanics, cabling and electronics. They also prevent easy access for debugging in final working conditions. The overall dimensions are 7.5 (14) cm inner (outer) diameter and 25 cm in length. The outer diameter is limited by the cold bore of the superconducting solenoid. The inner diameter is limited by the size of the cryogenic vessel containing the electrodes of the nested Penning trap. The innermost part of the detector of thickness less than 10 cm contains two layers each of 16 double sided silicon μ-strip modules, 16.2 cm long. The crystals with dimensions $17 \times 17.5 \times 13 \text{mm}^3$ are grouped in 16 rows of 12, closely filling the remaining space.

The μ-strip modules consist of two double sided sensors (SINTEF, $81.6 \times 19 \text{mm}^2$) with a wafer thickness of 380 μm glued onto a silicon mechanical support, and a multilayer ceramic hybrid, 2 mm thick.

The readout strips (139 μm pitch) are bonded to the pitch adapter integrated in the hybrid, itself bonded to a 128 channel chip glued on the hybrid. The 64 DC coupled pads ($1.25 \times 18 \text{mm}^2$) of the sensor $n$-sides are oriented perpendicular to the strips. Thin gold plated aluminum lines on the silicon support deliver the 128 signals to the bottom of the hybrid from where they are brought to a second chip VA2 TA via 128 feedthroughs in the ceramic.

Pure CsI scintillation crystals obtained from CRISMATEC are used to detect the 511 keV photons. The light yield is excellent at low temperature ($\approx 50,000$ photons/MeV at 80 K$^{38}$), and the decay time ($\approx 1 \mu s$) fits the shaping time of the front end electronics. The crystal light is seen by avalanche photo diodes (APD, Hamamatsu, type S8148, $5 \times 5 \text{mm}^2$), after carefully testing their low temperature functionality. A typical signal-over-noise ratio larger than 50 was achieved in spite of the smaller active area of the APDs, which is the limiting factor for the energy resolution ($\approx 18\%$ FWHM at 511 keV).

The APDs are also read out with VA2 TA chips. One chip is located at the end of a 230 mm long and 12 mm wide printed circuit board which connects the 12 APDs of one row to the 12 first input channels of the chip.

Outside the vacuum vessel, five repeater cards are plugged directly into the flange, which also serves as the main grounding point. Three of these boards, the digital repeater cards, house the main electronics for controlling the subdetectors. The cards are connected by two digital buses to standard CAEN VME modules.

Since no other active electronics could be placed in the cold section of the detector, the differential current output buffers of the chips drive the multiplexed analog signals over 1.5 m long cables of the same type as the digital lines. These signals are fed into receivers on two analog repeater cards on the vacuum flange. One pair of lines is used for each of the 256 channel μ-strip modules, while the
16 printed board circuits of the crystals share four lines. Differential line drivers send the 36 analog signals to 18 double channel FADCs (Caen V550) located in the same crate as the other VME modules. The crate is connected to the DAQ system running in LabView. Data (40 kByte/event) can be written to disk with a rate of typically 100 Hz. The block diagram of the detector is shown in Fig. 7. Shaping times for both detector components are set to $3 \mu s$, adapted to the time constant of light emission for pure-CsI.

The multiplicity coded trigger lines from the individual subdetectors (one line from each subdetector) can be recorded independently. The time jitter is typically 120 ns for the $\mu$-strips and 300 ns for the crystals. The trigger on pure photon events from $e^+$ annihilations is an essential component of the detector. The trigger signal is also needed to monitor the high instantaneous annihilation rates of antiprotons and positrons and for general diagnosis without full read out of the analog signals.

A 128 channel chip described in detail in Ref. 27 with a standard rms shaper ($\approx 2 \mu s$) and a second faster shaper ($\approx 75$ ns), is employed. The outputs of the fast shapers are fed to 128 discriminators with common threshold and programmable transition polarity.

The signal-to-noise ratio of the $\mu$-strip modules was about 40 on the strip and 50 on the pad side, respectively, measured with minimum ionizing particles at low temperatures. Charge loss on the floating strips was negligible. Cosmic data could also be used to determine the spatial resolution on the strip side.

In summary, the annihilation detector allowed to detect the impact points of the $\bar{p}$ annihilation products with a position resolution on the Si $\mu$-strips of $\sigma = 28 \mu m$, the $\gamma$ impact points on the crystal with resolution of about 1 cm, in a time window of $3 \mu s$. 

Fig. 7. Block diagram of the detector. Figure from Ref. 27.
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So far the ATHENA detector is still the only one that has been able of detecting both $\gamma$'s and charged particles from antihydrogen annihilations with this degree of precision in space and time.

3.7. Control and data acquisition

The control system is required to control all 27 electrodes of the mixing trap and the 11 electrodes of the positron transfer section, and to manage communication with the computers in charge of catching and cooling antiprotons and accumulating positrons when these particles are being transferred into the mixing trap.

Voltages on the electrodes of the mixing trap are supplied by two programmable triggerable 16 bits and 12 bits VME-based DAC’s with a buffer depth of 32k and 16k steps and one 100 kHz an 1 MHz, respectively. Voltages to the transfer electrodes, as well as triggers to the DACs, are supplied by two PCI-based 10 MHz programmable and triggerable 32-channel pulse generators. Additional fast (rise time $< 100$ ns) pulses of arbitrary shapes are provided by four 100 MHz 12 bit VXI-based waveform generators which could be connected to any of the 27 mixing trap electrodes.

A signal is used on two electrodes to apply 40 V/100 ns pulses generated by a 30 MHz GPIB-based pulser to mixed antiproton–electron clouds, in order to efficiently clean the antiprotons of electrons (at least 95% of the electrons are eliminated with four pulses). Transfers of antiprotons and positrons are managed by setting up dedicated sequences of voltages which are triggered by the remote computers, once handshaking has been established, at which point sequences steering the mixing of antiproton and positron clouds take over. These procedures are fully automated, and can repeat the same experiment an arbitrary number of times.

In addition to the central detector readout, scintillator pulse heights (determined by LeCroy 1182 ADCs), pulse shapes (recorded by INCAA VD71 transient recorders), and oscilloscope signals are acquired via VME and GPIB modules read-out by a LabView program, and written to a data base. The order in which the data are written to the data base does not necessarily correspond to the order in which events occur, since several modules contain multi-event buffers, and the control sequence for voltages and timings (which is downloaded to the data base before being executed) is not measured in real time. To retroactively establish timing, the heart of the DAQ consists of multi-hit time stamp units (one 8-channel and one 32-channel Struck SIS 3806) which record with up to 1 $\mu$s accuracy the time of each type of activity. Dead time-free acquisition is guaranteed internally by the use of two counter banks, one of which is active at any given time, while the data of the inactive bank is piped into a 64k FIFO. Switching between the two banks, which count the number of 100 ns intervals between switches, is triggered by an OR of all triggers. Triggers are generated by a 16-input VME general purpose programmable logic module combining all detector signals; this module allowed the simultaneous construction of a variety of trigger conditions.
Although the VME readout rate itself is bandwidth limited (corresponding to a detector readout rate of about 100 Hz), trigger rates up to a few MHz were reliably recorded for 32 types of triggers in parallel, and with a time resolution of 10 ms, by the 32-channel time-stamp unit. A higher time resolution of 1 μs was achieved for some triggers with the 8-channel time-stamp unit.

3.8. Event reconstruction

Data from the apparatus were analyzed in real time and saved on media by the DAQ program, which (a) reads and processes the raw data from the DAQ and (b) performs a quick analysis of the raw data during the runs. Because data are saved asynchronously as they are recorded by the detectors, the online software uses a hardware time stamp to reorder the events in the correct time sequence, to correlate data from the traps with data from the detectors.

The online data, in the form of a ROOT data tree, were then passed to the offline software that extracts the detector events from the tree and performs the event analysis.

The offline software decodes the detector response, reconstructs the interaction points of the particles in the inner and external silicon layers, associates the tracks to these two points (pattern recognition), finds the vertex of the charged particles and selects the crystals with 511 keV signals (the candidate crystals). A ROOT online monitor provides a display of the reconstructed events. Some batch macros give a set of histograms to control both vertex positions of the annihilations and detector performances. The hit coordinates of charged particles from the silicon μ-strip modules are found by standard clusterization algorithms applied to the pedestal subtracted ADC values. The hit coordinates are calculated from the μ-strip and z-pad information.

As already explained in Subsec. 3.6, one of the important goals is to verify if the angle between the two lines joining the charged particle vertex on the trap wall with two candidate crystals is equal to $\pi$ within errors (see Fig. 6). This configuration means both $\bar{p}$ and $e^+$ annihilations at the same point and time within the detector resolution and therefore is one of the signatures of $\bar{H}$ annihilation. To detect antihydrogen a good performance of the 192 crystal detector is crucial in order to assure correct reconstruction of the positron annihilation. During the experiments, the detector temperature was monitored continuously and the crystals were calibrated periodically with positron annihilation data coming from dedicated runs where the recombination trap was filled with positrons only.

We assign to each vertex a Quality Index (QI) calculated by assigning a score to each of the following good vertex properties: (1) a small vertex residual ($R \leq 0.4$ cm) defined as the sum of the distance of the tracks from the vertex divided by the number of the tracks; (2) a small discrepancy ($\leq 0.4$ cm) between the two vertex algorithms used in the reconstruction; (3) a good matching of the two vertices in all the 2D views; (4) more than two tracks; (5) a small distance ($< 0.1$ cm) between...
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Fig. 8. Two-dimensional reconstruction of the vertices on the mixing trap wall. The dimensions are in cm. The plots refer to Monte Carlo simulation of antihydrogen annihilation on the trap wall (ghMC), data from mixing at 15 K (Cold), data from mixing at higher temperatures (Hot). The best fit of the Cold plot data (Fit result) is obtained by fitting the Cold plot with the sum of the two histograms ghMC and Hot with adjustable weight. This allows to find the $\bar{H}$ and background percentages.

the inner silicon layer point and the line joining the external silicon layer point and the vertex. We have obtained a reconstruction efficiency from 61% to 7% ranging from a QI from 0 to 6.27 This is a good result, in agreement with MC simulations, if we consider that the tracks are reconstructed as straight lines joining the two $\mu$-strip modules, neglecting the curvature due to the magnetic field. Typical vertex plots are shown in Fig. 8, where the annihilations on the trap wall (a cylinder with radius $R = 1.25$ cm) are clearly evident in the case of $e^+$ and $\bar{p}$ mixing at low temperature (cold mixing). Many details on three-dimensional imaging of antiprotons in a Penning trap, obtained by reconstructing the annihilation vertices are given in Ref. 41 and Sec. 6.
The hit selection in the silicon $\mu$-strip detector and the vertex reconstruction strongly enhances $\bar{p}$ annihilation events with practically no background contamination. For the crystals, however, two main sources of background contribute: (i) short tracks from charged particles in the crystals and the conversion of high energy $\pi^0$'s lead to low energy background signals in the 511 keV region; (ii) positrons from showers generated in the surrounding magnet by high energy $\pi^0$'s also lead to 511 keV signals.

These background effects have been greatly reduced by means of particular $\bar{H}$ selection criteria, studied by extensive Monte Carlo (MC) data. Since the goal was to find clear signals of $\bar{H}$ annihilation, rather than to collect events with high efficiency, the procedure for $\bar{H}$ event selection, based on the high granularity of the detector, was as follows. Only events with a reconstructed vertex are considered. Reconstructed tracks are extrapolated toward the crystals and those hit by an extrapolation line are identified and excluded from the subsequent $\gamma$ detection together with their eight neighbors. Due to the limited efficiency, some tracks are not reconstructed and some isolated hits remain. Hence, also the crystals that lie above a hit on an external silicon layer module are considered as traversed by a charged particle and excluded as is its eight neighbors. After this first selection, crystals are scanned for having a signal within the 350–550 keV window and events with exactly two such crystals are selected. To reduce from this sample the fake $\bar{H}$ events due to the e.m. cascades from the surrounding magnet, also the requirement that the two selected crystals are not surrounded by other crystals with a signal above threshold is made. Therefore, the final sample consists of events with a reconstructed $\bar{p}$ annihilation vertex and two isolated crystals in the right energy window (the candidate crystals), with the possibility to have some other crystals in the detector with signals outside this window.

The distance between the line joining the center of the two candidate crystals and the reconstructed vertex is expected to be consistent with zero in $\bar{H}$ annihilations. This corresponds also to the condition $\cos \theta_{\gamma\gamma} = -1$ where $\theta_{\gamma\gamma}$ is the opening angle between the two lines joining the candidate crystals and the $\bar{p}$ vertex (see also Fig. 6). Therefore, the second $\bar{H}$ strong signature, in addition to the plots of Fig. 8, is the $\cos \theta_{\gamma\gamma}$ (opening angle) plot of Fig. 9.

In this figure the experimental data are compared with the result of MC simulations of annihilations based on the $\bar{p}$ and $e^+$ annihilations occurring at the same time and at the same position on the wall of the recombination trap. We also considered two types of background, (1) due to a $\bar{p}$ that annihilates on a residual gas atom in the trap volume and (2) due to $\bar{p}$ and $e^+$ annihilations at the same time but in two different locations on the trap wall, simulating the worst case of an $\bar{H}$ atom that loses its positron before annihilating.

The MC efficiencies for the $\bar{H}$ annihilations and for these two types of background are shown in Table 1. The simulation shows also that the relative efficiencies between the $\bar{H}$ signal and the backgrounds are independent of the QI of the reconstructed vertex.
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Fig. 9. (Color online) Left: Monte Carlo generated \( \cos \vartheta_{\gamma\gamma} \) distribution of the opening angle \( \vartheta_{\gamma\gamma} \) for the \( \bar{H} \) annihilation (bold line) and for the \( \bar{p} \)-annihilation background of type (1) (grey) and the uncorrelated \( \bar{p}+e^+ \) annihilation background of type (2) (hatched) (see the text). The peak at \( \cos \vartheta_{\gamma\gamma} = -1 \) is absent in both types of background. Right: the same distribution in the case of real data during the cold mixing of \( \bar{p} \) and positrons (bold line) and the same histogram (hatched) in the case of hot mixing without recombination. The \( \bar{H} \) and background distributions are normalized to the same number of reconstructed vertices.

Table 1. Real and MC efficiencies for events entering into the opening angle histograms of Fig. 9 (Entries) and into the first two channels, corresponding to \(-1 \leq \cos \vartheta_{\gamma\gamma} \leq -0.947 \) (Signal) following the selection procedure described in the text. The MC results are obtained starting from pure \( \bar{H} \) annihilations on the trap wall, \( \bar{p} \) annihilations in the open volume of the trap (background 1) and spatially uncorrelated \( \bar{p} \) and \( e^+ \) annihilations on the trap wall (background 2). The real data come from pure \( \bar{p} \) annihilations on the trap wall.

<table>
<thead>
<tr>
<th>( \bar{H} ) events</th>
<th>( \bar{p} ) background (1)</th>
<th>( (\bar{p})(e^+e^-) ) background (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>MC</td>
<td>data</td>
</tr>
<tr>
<td></td>
<td>((9.45 \pm 0.08) \times 10^{-2})</td>
<td>((6.35 \pm 0.08) \times 10^{-2})</td>
</tr>
<tr>
<td></td>
<td>((6.12 \pm 0.11) \times 10^{-2})</td>
<td>((1.9 \pm 0.1) \times 10^{-3})</td>
</tr>
<tr>
<td></td>
<td>((1.8 \pm 0.2) \times 10^{-3})</td>
<td>((4.6 \pm 0.2) \times 10^{-3})</td>
</tr>
</tbody>
</table>

The events and the signal in the Table 1 are defined as the number of entries in the opening angle histogram of Fig. 9 and that in the first two channels, corresponding to \(-1 \leq \cos \vartheta_{\gamma\gamma} \leq -0.947 \).

The MC histogram for \( \cos \vartheta_{\gamma\gamma} \) is shown in Fig. 9 (left), where a clear signal around the value \( \cos \vartheta_{\gamma\gamma} \approx -1 \) appears in the case of \( \bar{H} \) annihilations in agreement with the efficiencies reported in Table 1. Apart from this signal, the rest of the histogram shows a plateau of events due to the 511 keV \( \gamma \)'s from positron annihilations that have lost by scattering their original direction or to the accidental firing of crystals due to soft \( \gamma \)'s from the e.m. cascades into the magnet or other parts of the apparatus. Hence, it is important to note that the signature of the \( e^+ \)
annihilation, in the opening angle plot, is the whole shape of the histogram, not only the \( \cos \theta_{\gamma\gamma} = -1 \) peak.

When we mixed \( \bar{p} \) and positrons in the recombination mixing trap at low temperature (cold mixing) we obtained a clear \( \bar{H} \) formation signal, shown with the bold line in Fig. 9 (right). In the same figure, the hatched histogram shows the distributions obtained with the recombination completely stopped by heating the positron plasma with a radio-frequency (RF) signal. These results show clearly the ATHENA apparatus is still the unique one that allowed the detection of \( \bar{H} \) production by means of the space–time coincidence of \( \bar{p} \) and \( e^+ \) annihilations, disentangling this signal from other processes and from the various sources of background.

As an example of this kind of analysis, we show in Fig. 10 the two-dimensional deconvolution of the vertex spectrum “Cold” in Fig. 8 which represent the vertices reconstructed by the detector when \( \bar{p} \) and \( e^+ \) are mixed at low temperature. We use here the iterative Van Cittert algorithm described in Ref. 42 where the apparatus function is a two-dimensional Gaussian with \( \sigma_x = \sigma_y = 0.3 \) cm which represents the resolution of the vertex algorithm. The deconvolution shows clearly two distinct structures in the \( \bar{p} \) annihilation vertices: a peak around the trap axis and a uniform population on the trap wall.

![Deconvolution of the two-dimensional plot “Cold” of Fig. 8 with the Gaussian point spread function representing the resolution of the vertex algorithm.](image)

**Fig. 10.** Deconvolution of the two-dimensional plot “Cold” of Fig. 8 with the Gaussian point spread function representing the resolution of the vertex algorithm. In the inset the cosine of the opening angle in correspondence of the annihilation zones indicated by the arrows is shown (plots (a) and (b)). The plot (c) correspond to hot mixing.
The peak at the trap center is studied in Sec. 9, where it is shown that the data are consistent with protonium $\bar{p}p$ annihilations, as a result of the $\bar{p}$ interaction with the molecular $H_2^+$ of the residual gas. This system is neutral and escapes from the confining fields, but decays before arriving to the trap wall. In effect, the inset of Fig. 10 shows that the peak at $\cos \theta_{\gamma\gamma} \simeq -1$ is missing, indicating the absence of $e^+$ annihilations.

On the contrary, on the trap wall, the annihilation vertices are associated to an opening angle plot which shows clearly the presence of the $e^+$ annihilations, indicating the formation of stable $\bar{H}$ atoms and their escaping.

By exploiting the detector performances, ATHENA has been able to study in great detail the conditions of the $\bar{H}$ formation and their dependence on some important physical parameters. These results are described in detail in the following sections.

4. Antiproton Accumulation and Cooling

Once trapped in the catching trap, the antiprotons oscillate back and forth between the two extreme electrodes where the high voltage is applied. There are not efficient self-cooling mechanisms for trapped antiprotons: the cooling by the emission of radiation is negligible (due to the high mass of the antiprotons) and the collisions with the residual gas have a very low rate (due to the extreme vacuum reached in the trap environment) and they finally would originate losses of antiprotons.

An external cooling mechanism has to be introduced in the trap: we have used with success the electron cooling method. Electrons are preloaded in a region few cm long of the catching trap before the injections of antiprotons. We routinely stored more than $10^8$ electrons in a potential well of few tens of eV using a fraction of the length of the catching trap. The light electrons, conversely to antiprotons, cool themselves very efficiently in the 3 T magnetic field by synchrotron radiation. The time constant for the cooling of the electron radial motion is 0.4 s. Coulomb collisions between electrons lead to a cooling of the axial motion too and collisions between antiprotons and electrons efficiently cool the high energy antiprotons; this process heats the electrons but they continue to lose energy by radiation. Finally, if the number of electrons and their density are sufficiently high, the two species reach a thermal equilibrium distribution in few tens of seconds. Ideally the final equilibrium temperature is equal to that of the environment. The process can be modeled by two rate equations as discussed in Ref. 27 that predicts that $\simeq 10^4$ antiprotons having energies in the keV range can be cooled down to less than a few eV within a few tenths of a second if they overlap completely with an electron cloud of density around $10^7$–$10^8$ cm$^{-3}$. Our results are in good agreement with this prediction.

The efficiency of the cooling process is studied by dumping the “hot” antiprotons from the high voltage well and then later the “cold” antiprotons cooled by the electrons and captured in the narrow internal electron well. Figure 11 shows a typical
Fig. 11. A typical antiproton annihilation time spectrum measured by the external annihilation detector for two values (5 s and 20 s) of the cooling time between antiprotons and electrons. The clock is started at injection of the antiproton beam into the trap. The left side of the plot schematically shows the trap voltages during the electron cooling process.

time distribution taken with the external annihilation detectors (see Subsec. 3.4) for trapped antiprotons released and annihilating on the degrader at the entrance of the trap. The electric potential was first lowered from 5 kV to 40 V (with a time constant of $\approx 20$ ms) releasing the higher energy antiprotons ("hot dump" at the time $T_1$ in Fig. 11), and then from 40 to 0 V in about 1 ms starting at the time $T_2$ thus releasing the antiprotons which had been cooled ("cold dump"). The fraction of cold antiprotons increases with the cooling time $T_2$ as Fig. 12 shows. Nearly all antiprotons are cooled in about 60 s.

Since the catching process does not influence the potentials within the central region where the cold antiprotons and the electrons are collected, several AD shots can be stacked in the catching trap. The number of stacked AD shots that optimized the antihydrogen production sequence was three: in fact during the time necessary to catch and cool three AD shots, the number of accumulated positrons reached its regime value.

Cold antiprotons are transferred toward the mixing region by adiabatically moving the electrode voltages along the traps. The transfer efficiency in the case when electrons and antiprotons are moved together have been compared with those when electrons are first ejected from the catching trap and only the cold antiprotons are transferred. Transfer efficiencies greater than 90% are obtained when electrons and antiprotons are transferred together while a dramatic decrease in the transfer
efficiency has been observed if cold antiprotons are moved alone.\textsuperscript{27} Therefore, the $\bar{p}$ are transferred in the mixing trap together with electrons, in spite of the shorter storage time in the catching trap (see Fig. 5).

While the number of cold antiprotons stored in the catching trap linearly increases with the number of AD shots, under the experimental conditions of 2002 the transfer efficiency did not follow the same behavior. Thus when stacking several shots in the catching trap prior to transfer, most of the transferred antiprotons (about 75\%) originated from the last trapped bunch. This behavior was unexpected and could be related to possible radial separation of antiprotons and electrons leading to instabilities during the transfer. An improvement in the electron loading and especially the antiproton transfer procedure during the successive years of data taking has solved this problem. The number of antiprotons available for mixing was typically of the order of $10^4$.

5. Positron Accumulation and Cooling

The trapping scheme utilizes nitrogen buffer gas to trap and cool the positrons. Initial trapping occurs during the first passage of the positron through the trap electrodes by electronic excitation of the nitrogen gas. Such a transition is favored in nitrogen compared to positronium formation, which is the only other major inelastic channel open at our kinetic energies. After trapping, axial confinement is provided by applying appropriate electric potentials to the electrode array, whilst the radial confinement is provided by a 0.14 T axial magnetic field. Once trapped, the positrons continue to lose energy in collisions with the gas, finally residing in the potential well formed by the voltages applied to the large diameter trap electrodes.
Since the compression leads to heating of the plasma, and since the magnetic field in the trap is too low for efficient re-cooling by synchrotron radiation, another cooling mechanism has to be used. The nitrogen buffer gas already present in the trap has been successfully used to provide this cooling, despite the fact that this gas has a poor positron cooling rate. The presence of the segmented electrodes in the accumulation trap allows rotating wall compression during positron accumulation. This reduces positron losses due to cross-field transport in the presence of the buffer gas, leading to a larger number of accumulated positrons.

To monitor the performance of the positron accumulator, a segmented Faraday cup detector situated outside the main magnet and a calibrated CsI-photodiode detector to monitor the annihilation signal generated when the positrons strike the Faraday cup are used.

An optimization programme was undertaken to tune the performance of the system. The electrode potentials and buffer gas pressures have been varied, tuning the alignment of the magnetic field to the physical axis of the system. Figure 13 shows the end result, the accumulation of more than \(10^8\) positrons in a few minutes. When using a suitable frequency and amplitude for the rotating wall compression and applying this signal for the last 50% of the accumulation time, the lifetime of the positrons can be doubled in the presence of the buffer gas whilst maintaining the same accumulation rate. The data using the rotating wall compression (Fig. 13) are fitted with a lifetime of 200 s whilst the data without the rotating wall give a lifetime of 95 s. It is important to stress that these results occur with the buffer gas still present in the trap. The increase in lifetime with rotating wall compression...
shows that annihilation on the gas is not the dominant loss. This points instead to plasma loss due to collision-induced cross-field drift to the electrodes.

With the help of nondestructive plasma mode diagnostics, the rotating wall technique has been tuned and a wide range of $e^+$ plasma shapes (aspect ratio $6.5 \leq \alpha \leq 80$) and densities ($1.5 \times 10^8 \leq n_e \leq 7 \times 10^9 \text{ cm}^{-3}$) have been obtained.\textsuperscript{45}

Figure 14(a) shows measured ratios between signals from the central region of the Faraday cup with and without rotating wall compression. The central region covers about 20% of the total area. The direction of rotation of the applied electric field coincides with that of the natural rotation of the plasma. Figure 14(b) shows the corresponding total number of positrons observed by the CsI photodiode detector. The data in Fig. 14(a) exhibits a broad enhancement in the compression in the frequency range 300–600 kHz increasing with amplitude. The fact that the ratio for the central region rises above unity means that parts of the positron plasma which initially missed the Faraday cup, e.g. due to cross-field transport, have been compressed into the central region. Above 600 kHz an abrupt fall-off occurs which coincides with a similar decrease in the total number of stored positrons. Up to 600 kHz the total number of positrons is very stable for all amplitudes.

The data in Fig. 14 indicate a compression of about 2.5. However, the true compression turns out to be larger. The central region of the Faraday cups contained five individual plates, of which only three actually recorded a signal when the rotating wall is used. By examining ratios between adjacent plates and comparing to similar data when the Faraday cup was moved slightly off axis, it was possible to derive the position and size of the plasma.

6. Annihilation Imaging of Trapped Antiprotons

The ability to reach very high densities and very low temperatures of the positrons in the trap is one of the key features in ATHENA, together with the excellent detector performances in the reconstruction of the annihilation positions of both
antiprotons and positrons. An extensive study of the dynamics of the trapped particles during cooling was performed in preparation of the recombination runs in order to optimize the number of stored particles and to maximize the antihydrogen yield.

The motion of particles stored in a Penning trap is complex and is in general described by the so-called “geonium” theory,\textsuperscript{46} that takes inspiration from the motion of a bound system, like earth, but with the source of the binding field which is external to the system. If the external fields are a magnetic field and an electric field in a configuration like ATHENA, the motion of a charged particle is confined both axially (by the electric field) and radially (by the magnetic field).

The equation of motion can be solved to give an overall motion which is a superposition of three different oscillations: a magnetron motion, a cyclotron motion and an axial oscillation with different frequencies related by $\omega_m \ll \omega_z \ll \omega_c$ (Fig. 15).

In ATHENA, assuming that antiprotons are in complete overlap and in thermal equilibrium with the electron plasma at 15–40$^\circ$K this relationship is well verified: in a 3 T magnetic field the antiproton cyclotron frequency is 46 MHz and the single particle axial and magnetron frequencies for the harmonic trap are 490 and 2.6 kHz, respectively.

Beginning with pioneering works in the 1980s,\textsuperscript{47,48} radial particle transport across the magnetic field lines in a trapped plasma has been the subject of considerable research,\textsuperscript{47-49,52-56} since it sets a practical limit on the plasma confinement time. O’Neils confinement theorem\textsuperscript{57} states that, for an axially symmetric system, due to the conservation of canonical angular momentum, the mean-square radius of the ensemble of charged particles is approximately conserved. It is now well established that radial transport in the low pressure regime is driven by small trap imperfections and field misalignments that break the axial symmetry of the system.\textsuperscript{49} However, little attention has been paid to the particle dynamics in the proximity of the wall. With the first direct observation of particle losses at the wall, ATHENA probed this previously unexplored final step of the radial transport, and
showed that antiproton radial loss occurs in a manner that is highly nonuniform both axially and radially. In addition to their importance for antihydrogen production and detection, these observations may apply to charged particle loss in Penning traps in general. In fact Penning traps have been used in many areas of both pure and applied research, from precision spectroscopy to quantum information, as well as for antimatter confinement.

While various diagnostic techniques exist for trapped particle and plasma studies, imaging can give direct information about the particle cloud properties. A common technique of dumping the particles on a phosphor screen or collimated Faraday cup gives the radial cloud profile (perpendicular to the magnetic field axis), but the axial information is integrated out. For studies of trapped atomic ions, laser fluorescence techniques can be used for imaging, yet this method is not applicable to elementary (anti)particles. Direct imaging can be obtained by exploiting the annihilations of antiprotons: each annihilation produces about three charged pions on average, and these are detected with the ATHENA antihydrogen detector.

Depending on the residual gas densities and particle dynamics, the annihilation can take place either on the gas or on the trap wall. We focus our attention on radial loss processes, exploiting the distinctive capability of imaging antimatter particles. In a sufficiently high vacuum, where annihilation on the residual gas is negligible, antiparticle annihilation imaging has unique sensitivity to losses at the trap walls. No other techniques have yet allowed such direct observations of charged particle losses in traps.

Figure 16(a) shows an image of antiproton annihilations in a harmonic potential well of depth 30 V and length 5 cm. With a relatively high gas pressure of the order of $10^{-11}$ mbar (estimated from the antiproton storage lifetime of a few hundred seconds), annihilation on residual gas atoms (or ions) dominates. The image thus reflects the profile of the trapped antiprotons at the time of their annihilation, an axially symmetric distribution as expected. Striking features in the annihilation pattern are observed in Fig. 16(b), where the residual gas density is reduced to less than $10^{-13}$ mbar with other conditions kept similar. In this case, the radial loss on the wall dominates over annihilation on the gas. The observed annihilation distribution is strongly anisotropic, and is localized to a few “hot spots.” The localization of antiproton loss at the trap wall is a general feature observed by ATHENA in the high vacuum regime.

Detailed MC simulation studies were performed in order to quantitatively understand the images obtained. The MC code simulates the interaction of the annihilation products with the detector and the surrounding materials. It utilizes the branching ratios and the decay phase space for antiproton annihilations on protons, and simulates full e.m. and hadronic cascades. The detector geometry and its module-by-module efficiencies are taken into account. Generated events are passed through the same analysis program as the annihilation vertex reconstruction. Figure 17 compares the radial distribution for the high vacuum case and that from
Fig. 16. Annihilation image of antiprotons trapped in a harmonic trap for (a) high pressure and (b) low pressure. The harmonic potential is formed with five central and two end cap electrodes. The estimated position of the trap wall is depicted with a white line. Figures from Ref. 41.

Fig. 17. (Color online) (a) Comparison of radial \((r)\) annihilation distributions \((dN = r\,dr)\) for the data from the low pressure measurement (error bars) and the MC simulations assuming annihilations on the trap wall (brown histogram). The inner radius of the trap electrodes is indicated with a dashed line. Also shown are the data for the high pressure measurement (grey histogram). (b) The azimuthal \((\phi)\) angular distribution of the annihilation (error bars) and its comparison with the MC assuming point source annihilation. Figures from Ref. 41.

the MC assuming a point source of annihilation on the trap wall. The good agreement establishes that most of the annihilations are indeed occurring at the wall. Also shown is the radial distribution for the high pressure case, which is clearly distinguishable from that representing annihilation on the wall.
The localization of the antiproton loss at the wall is observed in the high vacuum regime, irrespective of other trap conditions. We illustrate this in the following example. Figure 18 shows antiprotons trapped in a well formed by a single electrode: the annihilation distributions are strongly correlated with the trap well positions, as expected. The observed annihilations, however, are highly nonuniform both axially and azimuthally, as before. In the $z$ projection, annihilations are seen to cluster mainly at the edges of the electrodes. The number of hot spots grows with the number of the electrodes used in the well.

The ATHENA observation that the (charged) antiproton losses on the wall are localized to hot spots, while the neutral antihydrogen annihilates in a radially symmetrical manner, can provide a new and effective signature of antihydrogen annihilation, based on the charged vertices alone (without relying on the 511 keV $\gamma$ detection). This technique, applied to other trap systems, substantially simplifies the detection system necessary in the current\cite{65,66} and future antihydrogen experiments.
7. Plasma Modes Diagnostics

Knowledge of the characteristics of the trapped positron cloud is important for many reasons. The antihydrogen formation reactions taking place when antiprotons and electrons are mixed have very different functional dependencies on both density and temperature. Moreover, the space charge of a sufficiently dense positron cloud considerably alters the effective electrostatic potential and the dynamics of the interaction between antiprotons and positrons.

Positrons and electrons trapped in various region of the ATHENA traps behave as nonneutral cold plasma. In fact their density and temperature are such that the Debye length is smaller than the cloud dimensions and then collective effects largely dominate the dynamics. Nonneutral plasma in Penning or Malmberg trap are widely studied. Both theory and experiments have established that in the thermal equilibrium state a cold plasma forms a cloud whose shape has rotational symmetry with almost constant density and sharp edges: the density falls to zero within few Debye lengths. In particular for a harmonic Penning trap, the cold plasma can be described like a low temperature spheroid with constant density $n_e$ and characterized by the aspect ratio $\alpha = z_p/r_p$ where $z_p$ and $r_p$ are the axial and radial axis, respectively. Small perturbations from the equilibrium state excite plasma modes whose frequencies have been analytically calculated for a plasma in the zero temperature limit in a Penning trap. Experimental work has confirmed the relationship between the frequencies of the dipole and quadrupole modes (the first two low order axial modes) and the density and the aspect ratio. The measurement of the mode frequencies only do not allow to know the radius of the plasma, or in equivalent way, the total number of particles. ATHENA has developed a novel model to describe the relationship between the plasma length and the shape of the resonance in the plasma response in correspondence of the excited axial modes. Using this technique, aspect ratio, density, and length are measured. Hence the radius and the total number of particles can be obtained. In summary, the full information on the plasma properties is accessible with a minimal amount of perturbation on the $e^+$ plasma and in a not destructive way: the plasma can be monitored without dumping it. The details are discussed in Refs. 40 and 70.

Being the frequency of the quadrupole mode depending on the temperature of the plasma, one could monitor induced changes in the temperature of the plasma. This diagnostic has allowed the experimental study of the antihydrogen formation rate as a function of the plasma temperature (see Subsec. 8.4). The procedure was also useful in the characterization of the electron plasma used for antiproton electron cooling and thus for an optimization of the cooling process.

A custom hardware to excite the dipole and quadrupole modes by applying a sinusoidal perturbation to one electrode with an electromotive force $V_i = v_i e^{j\omega t}$ has been developed. The oscillation of the plasma induces a current in the pick-up electrode and a voltage $V_r = v_r(\omega)e^{j\omega t}$ is detected across the resistance $R_r$ (see Fig. 19). Experimentally the ratio $T_L(\omega) = v_r(\omega)/v_i$ is measured as a function of the
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Fig. 19. (a) Trap electrodes with the heating and mode detection electronics. The shape of the positron plasma prolate ellipsoid is shown schematically. (b) The axial potential of the ATHENA nested trap is shown and the ranges of axial motion of the positrons and the antiprotons indicated schematically. Figures from Ref. 70.

Drive frequency $\omega$. A narrow step-wise frequency sweep is made of the voltage source across the resonance frequency of each mode. The typical excitation amplitude $v_t$ is of the order of 100 $\mu$V and the dwell time for each 5 kHz step is 3.96 ms. The number of scan steps is usually 50. The plasma number density $n_e$ and aspect ratio $\alpha$ can be extracted from the zero-temperature analytical model\(^\text{71}\) using the measured frequencies $(\omega_1, \omega_2)$ of the dipole and quadrupole modes. An equivalent circuit model which explicitly includes the plasma dimensions and allows to get the plasma length when $\alpha$ and $n_e$ are known has been developed. The model describes the signal induced on an electrode by the coherent oscillations of the dipole mode when an external driving force is applied including the effects of the length of the plasma. In particular we obtain\(^\text{40}\)

$$T_L = \frac{g_l(\alpha, z_p)g_r(\alpha, z_p)R_e}{R_s + j\omega L(1 - \omega_1^2/\omega^2)},$$  \(1\)

The dimensionless functions $g_r$ and $g_l$ depend on the shape of the plasma and on the geometry of the trap and they can be easily calculated.\(^\text{70}\) They describe the effects of the finite plasma extension both on the mode excitation and detection. $T_L$ is obtained by measuring $T_L' = AT_L$ where $A$ is the net gain of the electronics.
chain. The inductance $L$ of the equivalent circuit is related to the plasma length,\(^{40}\)

$$L = \frac{3\alpha^2 r_w^2 m}{\pi n_e^2 z_p^3}, \quad (2)$$

where $m$ is the $e^+$ (or electron) mass and $r_w$ is the trap radius. The resistance $R_s$ characterizes the damping rate of the mode and it is obtained by fitting the width of the resonance line-shape. $\alpha$ and $n_e$ are determined independently by the frequency analysis. The power transmitted through the plasma $|T_L|^2$ is related to $R_s$ and $z_p$ by Eqs. (1) and (2). Thus, a fit to the measured transmitted power yields $z_p$. The radius $r_p$ and the total number $N$ can now be found.

The results on the $N$ measurement are in agreement with the signal of the Faraday cup (Fig. 20).

Plasma heating is implemented by applying an excitation near the dipole frequency (21 MHz) to one of the trap electrodes. Off-resonance heating pulses were not effective. The excitation is a variable amplitude signal that is swept from 20 MHz to 22 MHz at a repetition rate of about 1 kHz. Application of the excitation results in a rapid, voltage-dependent rise in the quadrupole frequency. When the excitation is removed, the quadrupole frequency returns to a value in step with the evolution of the unperturbed plasma. The unperturbed plasma evolution is characterized by a slow decrease in the frequency of the quadrupole mode and corresponding decrease in aspect ratio and density. This is consistent with a slow expansion of the plasma. Figure 21 shows the response of the plasma quadrupole frequency during heating off/heating on cycles with different amplitudes $V_d$ of

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Fig. 20. The total number of positrons obtained using the modes diagnostic is plotted against the number obtained by extracting the positrons to a Faraday cup. Figure from Ref. 70.
generated heating voltage. Thus the dependence of temperature increase $\Delta T$ on $V_d$ was found and the result is shown in Fig. 21(b).

8. $\bar{H}$ Production Mechanisms

In ATHENA, $\bar{H}$ can be produced by two fundamental processes: spontaneous radiative recombination (SRR) of positrons with antiprotons

$$e^+ + \bar{p} \rightarrow \bar{H} + h\nu,$$

(3)

which is the inverse reaction of the photoelectric effect, and three-body recombination (TBR)

$$e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+,$$

(4)

which is the inverse reaction of the ionization by collision.

Radiative formation depends on the positron temperature as $\simeq 1/\sqrt{T}$ and on the positron density as $\simeq n_e$ and results predominantly in atomic levels with low principal quantum numbers. The three-body formation becomes competitive at cryogenic temperatures (its dependence is $\simeq 1/T^{4.5}$) and at high positron densities ($\simeq n_e^2$); it mainly populates atomic levels with high principal quantum numbers. De-excitation to the ground state is slow and the nascent atom is susceptible to ionization by electric fields.

Prior to recombination, the positrons occupy a narrow band of states (corresponding to their temperature) in the ionic continuum of the yet-to-be-formed atom, whereas the antiprotons, due to their much larger mass, can be considered at rest in the positron gas. In a cryogenic trap environment, the $e^+$ kinetic energy $E_e$ is
typically much smaller than the binding energy \( E_0 \) of the atomic ground state. Under these circumstances, the SRR cross-section of Eq. (3) for capture to a state with principal quantum number \( n_H \) can be expressed in analytic form as: \[ \sigma_{\text{SRR}}(n_H, E_e) = (2.10 \times 10^{-22} \text{ cm}^2) \frac{E_0^2}{n_H E_e (E_0 + n_H^2 E_e)}. \] (5)

The total cross-section \( \sigma_{\text{SRR}}(E_e) \) is the sum over all \( n_H \) states up to some cutoff, which is usually given by collisional or field reionization of weakly bound states. It follows directly from Eq. (5) that capture into low-\( n_H \) states is favored by the SRR process. The recombination rate is obtained by integrating over the phase space overlap between the positrons and antiprotons: \[ R_{\text{SRR}}(n_H, E_e) = \int \sigma_{\text{SRR}} f(\vec{v}) v d^3v \int n_e(\vec{r}) n_p(\vec{r}) d^3r \equiv \alpha_{\text{SRR}} \int n_e(\vec{r}) n_p(\vec{r}) d^3r, \] (6)

where \( f(v) \) is the distribution of the positrons and antiprotons relative velocity \( v \), and \( n_e \) and \( n_p \) are their respective spatial densities. The first integral is called the recombination rate coefficient \( \alpha_{\text{SRR}}(v) \) and has been calculated for a spherically symmetric Maxwell–Boltzmann distribution, as well as for a so-called flattened distribution where the relative velocities in one dimension greatly exceed those in the perpendicular plane. In the case of a spherically symmetric velocity distribution, the temperature dependence has a leading \( T^{-1/2} \) term. When a correction for the aforementioned cutoff in \( n_H \) is applied, an overall dependence of the rate coefficient (and hence, the total rate) on the temperature of \( \alpha \propto T^{-0.63} \) is found. \[ \alpha_{\text{SRR}} \propto T^{-0.63} \]

The integrals of Eq. (6) are valid also in the case of the TBR of Eq. (4), but the recombination cross-section cannot be determined analytically. However, using a classical-trajectory MC simulation, the TBR rate coefficient is numerically calculated, again assuming a spherically symmetric velocity distribution, to be: \[ \alpha_{\text{TBR}} = \frac{(2 \times 10^{-27}) \text{ cm}^6 \text{ s}^{-1} n_e \left( \frac{1 \text{ eV}}{k_B T} \right)^{-4.5}}{k_B T}, \] (7)

where \( k_B \) is the Boltzmann constant. The inclusion of an external magnetic field reduces the rate by roughly an order of magnitude. Three-body recombination produces Rydberg atoms with principal quantum numbers \( n_H \gg 10 \). These excited states rapidly decay to the ground state, but can also be reionized by collision or by the strong electric fields present near the electrodes in the mixing region. Under real experimental conditions, an equilibrium between de-excitation and reionization is expected to set in. Below a “bottleneck” threshold binding energy of \( \simeq 4k_B T \), atoms become resilient to collisional ionization. The temperature dependence of the TBR rate coefficient is due to the fact that the rate is proportional to the square of the characteristic length scale of the reaction, the Thomson radius \( b = 2e^2/3k_B T \),
which is the distance between two elementary charges at which the potential of their Coulomb interaction is equal to the thermal energy. In these conditions the formation probability is proportional to the collision frequency $n_e b^2 v_e$ times the encounter probability, which is proportional to $n_e b^3$. Therefore

$$R_{SRR}(n_H, E_e) \propto (n_e b^2 v_e)(n_e b^3) \propto n_e^2 T^{-9/2}. \quad (8)$$

If we assume complete overlap between $\bar{p}$ and $e^+$, we can define two (in general time-dependent) rates for the evolution of the $\bar{p}$ population $n_p$, one for detected antihydrogen $\lambda_d$ and one for antiproton loss through field ionization or collisions $\lambda_i$:

$$\frac{dN_d(t)}{dt} = \lambda_d n_p(t), \quad \frac{dn_p(t)}{dt} = - (\lambda_d + \lambda_i) n_p(t), \quad (9)$$

where $N_d$ is the number of $\bar{H}$ atoms detected up to the time $t$, while $n_p(t)$ is the number of antiprotons still in the trap at time $t$. From the equations above, in the case of complete overlap, we have:

$$\lambda_d(TBR) = \alpha_{TBR} n_e \propto n_e^2 T^{-4.5} \quad \text{or} \quad \lambda_d(SRR) = \alpha_{SRR} n_e \propto n_e T^{-0.63}, \quad (10)$$

in the case of pure three-body or two-body recombination.

If we use the ATHENA mean value for the positron plasma density, $n_e \simeq 5 \times 10^8 \text{ cm}^{-3}$, for $T = 15 \text{ K}$, we obtain:

$$\lambda_d(TBR) \simeq 0.5 \text{ s}^{-1}, \quad \lambda_d(SRR) \simeq 0.035 \text{ s}^{-1}, \quad (11)$$

where, in the case of TBR, a factor 10 of reduction has been considered for the presence of the 3 T magnetic field.

Therefore, the steady states the two reactions of Eqs. (3) and (4) have very different dependence upon the temperature and the positron plasma density. Thus, at first sight, it would appear to be easy to distinguish between them. Furthermore, we have already noted that the two reactions produce very different distributions of bound states. The radiative process is a dipole-allowed free-bound transition which favors the capture of the positron into strongly bound states. By contrast, the three-body case is expected to favor weakly bound $\bar{H}$ since the reaction is essentially an elastic encounter of two positrons in the vicinity of the $\bar{p}$ with a "bottleneck" binding energy. Such weakly bound states are expected to be dramatically influenced by the ambient fields of the Penning traps.

For these reasons the comparison of the ATHENA production data with the theory is not easy and should require the precise knowledge of the overlap of the $\bar{p}$ and $e^+$ spatial distributions, their evolution during the confinement in the nested trap, the evaluation of the $\bar{H}$ ionization by field effects or by collisions. Some of this information is available, for the first time, from ATHENA data and can be compared with some theoretical calculation and simulation of the recombination processes in Penning traps. In the remainder of this section we will report the status of the present knowledge on this topic.
Before discussing the ATHENA results, we recall that the standard mixing at low temperature, called cold mixing, consists of the following steps (see also Subsec. 3.5):

(i) $\bar{p}$ are caught in the catching trap;
(ii) electrons are loaded in the catching trap to thermalize $\bar{p}$;
(iii) the positrons are transferred in the nested region of the mixing trap. A high density (2–6 $\times$ 10$^8$ cm$^{-3}$) spheroidal positron plasma with a length of 30 mm and a diameter of 4–8 mm is formed. The average positron plasma characteristics measured during the cooling measurements using a plasma mode analysis technique$^{40,70}$ were: radius $\simeq$ 2.8 mm, density $\simeq$ 1.1 $\times$ 10$^8$ cm$^{-3}$ and aspect ratio (ratio between the major and minor axis of the ellipsoid) $\alpha \simeq$ 5.5;
(iv) $\bar{p}$ and electrons are transferred into the mixing trap and are kept separated from positrons;
(v) electrons are kicked-out from the mixing trap by applying e.m. pulses to two electrodes (see Subsec. 3.7);
(vi) about $10^4 \bar{p}$ are transferred to the nested region of the mixing trap; start of the mixing time $t$;
(vii) the potentials are released for the final dump after 70 < $t$ < 180 s.

We recall also the main physical parameters of ATHENA mixing operations (see also Sec. 3): the applied magnetic field was about 3 T, typical electric fields in the trap were in the region of tens of V/cm, the trap electrodes were held at a temperature of around 15 K (to which the positrons cool by the emission of synchrotron radiation in the strong applied magnetic field). There was the possibility to heat the positron plasma by the application of a RF signal to one of the electrodes surrounding the plasma; by exciting its axial dipole mode resonance (at around 20 MHz)$^{40}$ The resulting shift in the quadrupole frequency provides the magnitude of the plasma temperature change. When antiprotons are injected into a positron plasma heated up to 3000 K, antihydrogen formation is effectively suppressed.$^{1,77}$ This cycle is termed as hot mixing (see Sec. 5).

8.1. Antiproton dynamics during recombination

We begin the presentation of the ATHENA investigations on the $\bar{H}$ production mechanisms from the measurements of the $\bar{p}$ spatial behavior in the nested trap during $\bar{H}$ production.

In the ATHENA nested trap, cold positrons are confined in the region that constitutes the central well. We recall that the positron space charge flattens the on-axis potential in the mixing region (see Fig. 22(a) and Subsec. 3.3). The space charge potential has been calculated using the positron plasma parameters given by the mode analysis measurements.$^{36}$ For the purposes of discussion we will take this flattened level to be the zero of antiproton energy. Antiprotons with negative energies are axially separated from the positron cloud and cannot recombine. It
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Fig. 22. (a) Potential energy diagrams for antiprotons on the axis of the nested trap are illustrated both with (solid line) and without (dashed line) positrons. The energy regions I to III described in the text are indicated. (b) Potential energy diagrams at different radii. Figures from Ref. 36.

It is important to stress that the zero energy level is dependent on the applied and space charge potentials and varies across the radius of the trap. This radial dependence has been calculated and is illustrated in Fig. 22 where the nested potential configurations for different radii are shown.

To measure the energy spectrum of the antiprotons, the confining potential is reduced in steps as shown in Fig. 4 and the annihilations of the released antiprotons are recorded at each step by the charged meson detection of the external scintillators described in Subsec. 3.4.

The delay between the different potential configurations is $\simeq 100\ \mu s$ and the duration of every step is $\simeq 50\ \mu s$. The energy resolution is determined by the step size of the confining potential and is of the order of a few eV, depending on the detailed potential configuration of each step. The readout system has a dual pulse resolution of $\simeq 50\ \text{ns}$. The signals are then recorded with a multi-scalar module for the link of the delay of the dump with the antiproton energy in the nested trap.
prompt cooling delayed cooling

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Fig. 23. (Color online) Antiproton energy spectra for different interaction times. The interaction time is shown on the top. The horizontal thick red lines divide the three energy regions.

The antiproton dump takes place in two different stages, namely a left well dump (LWD, see Fig. 4(a)) and a subsequent right well dump (RWD, see Fig. 4(b)). In the LWD, all antiprotons with positive energies as well as those in the left well with negative energies are released sequentially. In the RWD, only those antiprotons in the right well with negative energies are released. The positrons are also released during the RWD. The above-mentioned procedure allows a single snapshot of the antiproton energy spectrum to be obtained. To derive the time evolution of the antiproton energy distribution during the cooling process, we performed series of measurements where the particles are dumped in a controlled manner at various predetermined times after injection. During these measurements the reproducibility of the positron plasma characteristics is assured by the mode analysis diagnostics.

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Figure 23 shows the results of measurements in which the antiproton energy is measured as a function of the interaction time during cold mixing. By integrating the appropriate equation of motion we have taken into account the correction to the antiproton energy due to the time-varying potentials during the ramp. This effect is often referred to as “adiabatic cooling” and here leads to a correction of no more than 10%. 27

As a control, a measurement was performed without positrons in the central well (labeled as “no e+” in Fig. 23); the antiprotons were dumped after \( \approx 180 \) s, which is the longest antiproton–positron mixing time used during the antihydrogen production runs. Note that all of the antiprotons are released during the LWD, they remain at the injection energy and the RWD is empty: no cooling is observed. This confirms that the procedure for removal of the cooling electrons, outlined above, is effective. We observe that antiproton cooling to the bottom of the lateral wells only occurs in the presence of positrons, and should not be mistaken for electron cooling.

The remaining spectra in Fig. 23 show the energy distributions for different interaction times.
In general, a redistribution of antiprotons from the injection energy to lower energies is a clear indication that cooling takes place. Qualitatively, the data separate into three distinct energy ranges: I, the injection and cooling region at about 15–40 eV (see these regions in the center and the scale on the left in Fig. 23), II, an intermediate region between 0 and 15 eV, and III, the negative energy region of the two lateral wells. The border between region I and II is chosen in a way that radial effects due to off-axis potential variations can be taken into account; under experimental conditions this assures that all the antiprotons that are in thermal equilibrium with the positron plasma but not on the trap axis are included in region II.

The measurements reported in Fig. 23 show that there are three distinct timescales of the evolution of the $\bar{p}$ population during mixing in the ATHENA Penning trap. In the first stage, for $t < 20$ ms, the injected antiprotons are rapidly cooled to region II. For intermediate times ($20$ ms $< t < 1$ s), the evolution is characterized by a loss of population in region II and a growth in the number of antiprotons in the lateral wells (region III), in which the antiprotons no longer have spatial overlap with the positrons. The transition zone between regions II and III is the energy range in which the antiprotons are near to thermal equilibrium with the positrons and therefore have a high probability of recombination. Finally, for $t > 1$ s, there is a slow feeding of antiprotons from region I into the other energy regions, resulting in all antiprotons ending up in regions II or III by about $t > 50$ s.

The next sections will discuss how to correlate the behavior of the $\bar{p}$ population discussed above to the $\bar{H}$ formation.

8.2. Identification of the $\bar{H}$ annihilation events

Here we present the main results of the standard ATHENA analysis to identify $\bar{H}$ annihilations through the information coming from the annihilation central detector described in Subsecs. 3.6 and 3.8.

In a first step, the vertex distributions are analyzed to determine the relative rates of the contributing components ($\bar{H}$ and $\bar{p}$-only annihilations). In a second step, this decomposition is combined with MC efficiencies and compared with measured opening angles, to confirm these assignments. Then, in Subsec. 8.3, the temporal evolution of the two components will be investigated, and compared with the detector trigger rates. All data are corrected for detector readout dead time based on the trigger rate at the time of readout and the experimentally determined average dead time for that trigger rate.

In Subsec. 3.8 we have shown that two components account for the cold mixing vertex distribution (Fig. 8). The main component corresponds to annihilations on the trap electrodes, and is characterized by an isotropic distribution on the inner surface of the electrodes around the trap axis, and a broad distribution along the $z$-axis, as expected for $\bar{H}$ annihilations. The second component is centered on the axis of the trap. Its longitudinal extent of 2 cm is incompatible with a point source.
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(since the z-vertex resolution is 4 mm), but is close to the 3 cm length of the positron plasma. These events are compatible with \( \bar{p} \) annihilations on positive ions trapped in the central region of the positron well (see also Sec. 9).

As shown in Fig. 8, we fitted the measured vertex distribution “Cold” of the cold mixing data as a linear superposition of the radial MC vertex distributions for antiproton annihilations on the trap electrodes (“ghMC” in Fig. 8) and of the hot mixing data (“Hot” in Fig. 8). The result of the fit is superimposed on the data in Fig. 8 and shown with the label “Fit result.” The fit describes cold mixing data as consisting to \((69 \pm 3)\%\) of \( \bar{H} \) annihilations on the trap electrodes and to \((31 \pm 3)\%\) of (centrally enhanced) \( \bar{p} \) annihilations from hot mixing.

This result is in fully agreement with a one-dimensional fit to the radial vertex distribution for cold mixing as the weighted sum of the radial distributions for hot mixing and for MC simulated \( \bar{H} \) atoms (uniformly generated from \( R = 1.25 \) cm and \( |z| < 1.5 \) cm and isotropically emitted) annihilating on the trap electrode walls.

In addition, we can verify the correctness of the ratio of the two components (annihilations on the electrodes and annihilations close to the trap axis), by using the opening angle plots described in detail in Subsec. 3.8. We generate MC events for the two components of the fit to the radial vertex distribution. The first component consists of \( \bar{H} \) annihilations on the trap electrodes, for which the \( \cos \theta_{\gamma\gamma} \) distribution corresponds to the light distribution in Fig. 24(b). The second component consists of \( \bar{p} \)-only annihilations at the center of the apparatus (Fig. 24(b), dark distribution). Note that neither the shape, nor the amplitude of the distribution changes if instead we simulate pure \( \bar{p} \) annihilations on the trap electrodes. The two components are normalized to the number of event resulting from the fit of Fig. 8.

Incidentally, we note that this simulation of antiprotons annihilating on the electrodes is in good agreement with the experimentally obtained \( \cos \theta_{\gamma\gamma} \) distribution for antiprotons intentionally annihilated on the trap electrodes.

The \( \cos \theta_{\gamma\gamma} \) distribution for these two MC data sets are added together, without any renormalization (light shaded histogram), and are superimposed on the experimental distribution of Fig. 24(a) (bold line). The prediction based on the radial vertex fit together with the simulations is in good agreement with the data. This is a strong indication that the assumptions that the annihilations on the trap electrodes correspond to \( \bar{H} \) events, while the central annihilations correspond to \( \bar{p} \)-only annihilations, are correct, and that consequently, around \( 2/3 \) of the events in the fiducial volume stem from \( \bar{H} \) annihilation. A fit of the distribution of Fig. 24(a) as a linear superposition of the two distributions of Fig. 24(b), has been used as an independent determination of the fraction of antihydrogen. The resulting value of \((60 \pm 5)\%\) is in good agreement with the values from the fits of the vertex distribution.

All these results are integrated over the full cold mixing cycle, that is over 70–180 s. The time structure of the production is discussed in the next section.

The efficiencies here estimated allowed the estimation of the ATHENA total production of \( \bar{H} \) as 900,000 antiatoms (with an uncertainty of about 5\%) with a
yield per injected \( \bar{p} \) of \((17 \pm 2) \%\), \(^{36,77}\) in agreement, as order of magnitude, with the percentage of 33\% coming from the simulations of the ATHENA nested trap dynamics based on the three-body recombination.\(^{78}\)

### 8.3. Time behavior of the \( \bar{H} \) production

The correlation between the different cooling phases and antihydrogen production can be studied by examining the background-corrected trigger rate or the reconstructed vertex rate of the annihilation detector as a function of time from the moment antiprotons are injected into the positrons.

Event triggers consist of at least three hits on either side of the outer silicon strip detectors. They initiate readout of both silicon and CsI modules. With the exception of the readout (dead time of 300 \( \mu \)s per event), the trigger rate is continuously recorded, as are the readout dead times.

On the other hand, the vertex distributions for the different data sets, is defined a fiducial region (radius \( R < 1.5 \) cm, \(-0.5 < z < 1.5 \) cm) centered on the positron plasma.

Trigger and vertex distributions are compared in Fig. 25. For each time slice, the radial vertex distribution for events in the fiducial volume is fit to the same measured components as in Subsec. 8.2: annihilations on the trap electrodes and hot mixing data. The result of the vertex fit in the different time slices is shown in Fig. 25(a). A noteworthy feature of the fits is that the time evolution of the two components is different, the antihydrogen component accounting for over 85\% of the vertices shortly after the beginning of mixing, with a slow decrease to around 50\% thereafter.\(^{77}\)
The time evolution of the trigger rate from the start of cold mixing is shown in Fig. 25(b), for the standard mixing conditions of $10^4$ antiprotons and $7.5 \times 10^7$ positrons. This distribution is characterized by a high initial value and a slow decay (with a timescale of several seconds). We compare this distribution with the time evolution of all events with reconstructed vertices by correcting the latter for detection efficiency. Two terms enter this correction: the probability for a triggered event to have a reconstructed vertex ((52 ± 2)%, as determined both from MC and real data) and the correction for vertices lying outside of the fiducial volume, but within the central volume ($|z| < 4$ cm) of the detector ((50 ± 3)%), as determined from the data. After these corrections, the time evolution of the trigger events with reconstructed vertices (Fig. 25(b), lightly shaded areas) is in reasonable agreement with that of the trigger rate. The slight discrepancy is consistent with neglecting vertices (probably due to antiproton losses at the end of the nested trap) which lie outside of the central volume of the detector ($|z| < 4$ cm), but contribute to the trigger rate. The reasonable agreement between the two distributions is an indication that the MC determination of detection efficiencies is correct, and that the temporal decomposition of the vertex distributions can be transferred to the temporal behavior of the trigger rate.

In contrast with the exponential behavior of the cold mixing trigger rate, the hot mixing trigger rates (not shown in the figures) have a flat distribution, which is about 10% of the initial cold mixing trigger rate. We have thus determined that $\bar{H}$ production comprises over 85% of the triggers at the beginning of mixing, and declines with a time constant of several seconds. Antiproton annihilation on positive ions or on rest gas (with a slowly decreasing rate) comprises the remainder of the triggers (15% at the beginning of mixing).
Integrated over a full mixing cycle of 180 s, antihydrogen production accounts for $(65 \pm 5)\%$ of the trigger rate, a result in agreement with the analysis of the previous section, which can thus be used as a proxy for fully reconstructed events.

The sets of data of Figs. 23 and 25 indicate three distinct timescales for the $\bar{H}$ production: prompt cooling, thermal equilibrium and slow cooling.

During the first phase of fast or prompt cooling ($t < 40 \text{ ms}$) the time constant of $\simeq 10 \text{ ms}$ for around 40% of the antiprotons is consistent with the $\simeq 4 \text{ ms}$ timescale that is expected for 40 eV antiprotons to thermalize, when taking into account the time spent outside the positron plasma. In effect, by following their dynamics during the fast cooling by means of a numerical code, we found that the $\bar{p}$ spend $\simeq 1/3$ of the total time inside the positron plasma. The cooling time is strongly dependent on the $\bar{p}$ relative velocity which explains its reduction between 10 and 20 ms. Once thermal equilibrium is approached the antiprotons are able to diffuse inside the positron cloud. Consequently, the time spent in the plasma increases, enhancing the antihydrogen formation probability. Indeed, it is at the end of the fast cooling period that the observed $\bar{H}$ production starts to rise rapidly and peaks after some tens of ms (inset Fig. 25(c)). The most likely explanation for the fact that only 40% of the antiprotons participate in this initial cooling is the incomplete radial overlap between the positron plasma and the $\bar{p}$ cloud.

Note that in the ATHENA experimental conditions, in the fast cooling process, the deposition of the entire kinetic energy of the injected $\bar{p}$ into the positron cloud would only raise the positron temperature by about 25 K without affecting their dynamics. This was confirmed by monitoring the plasma with the modes analysis technique (see also Sec. 7) and is confirmed by dedicated simulations. We have determined, with dedicated measurements at different initial heating temperatures, a decay time constant $\tau_e = 0.48 \pm 0.05 \text{ s}$ (see Ref. 80 and Subsec. 8.4). Therefore, we expect that the energy deposited in the positron plasma is removed by synchrotron radiation within $\simeq 1.5 \text{ s}$.

During the second phase of thermal equilibrium, we observe, from Fig. 23, that the distribution of cooled antiprotons shifts from region II to lower energies very close to zero and even begins to cross the on-axis potential characteristic of thermal equilibrium between $e^+$ and $\bar{p}$. This is the time at which we observe, in Fig. 25(c) a very rapid increase in $\bar{H}$ production. While the cross-over from region II to region III depends on the exact position of this border in the LWD, with its inherent calibration uncertainty ($\simeq 2 \text{ V}$ determined by the dump step size), it is clear also from the RWD that at around this time some antiprotons attain negative energies and are thus separated from the positrons. We suggest two possible contributing factors for this. The first one is the stochastic feeding of $\bar{p}$ into the lateral wells due to collisions that transfer energy from the longitudinal to the radial motion; the second one is the production of axially moving weakly bound Rydberg $\bar{H}$ atoms, which can be ionized at the longitudinal extremes of the nested potential, trapping the antiproton in the lateral wells.
Since in the ATHENA experimental conditions for the antiprotons one can estimate that the frequency of the first effect is of the order of a few Hertz, the more probable reason is that the lateral well antiprotons arise mainly due to ionized weakly bound Rydberg H atoms. Moreover, the observation that these antiprotons end up with energies in a narrow band just below zero, thereby coinciding with the maximum electric fields for stripping the weakly bound H atoms, would seem to corroborate the importance of this mechanism for producing axially separated antiprotons.

The third phase is the delayed slow cooling, that start for $t < 1–2$ s with the cooling of the antiprotons that still populate region I (radially separated) with a very long time constant. This slow cooling phase could be due to essentially two causes.

The first is the cooling in the tails of the radial distribution of the $e^+$ plasma, where the rate is much lower than in the plasma center. The radial tails have an extent equal to the Debye length which, at the ATHENA $e^+$ plasma density and temperature conditions, is a few tenths of microns. This cannot explain the large effect evident in the experimental data. However, it is possible that cold fluid theory might not be strictly valid for the ATHENA case of a two component plasma. It should be noted though, that centrifugal separation usually only deals with same sign charged plasmas. Understanding of the detailed dynamics of centrifugal separation for oppositely charged plasmas in a nested trap probably await additional theoretical work. The effect needed to explain the slow cooling observed in our measurements does not need to be very large. A relative density tail in the distribution of $10^{-3}$ to $10^{-4}$ over a length scale of the order of the plasma radius outside the $e^+$ plasma would be sufficient.

The second possible reason could be a slow radial expansion of the $e^+$ plasma that gradually envelops the initially radially separated antiprotons. This radial transport has been investigated in ATHENA. In our normal experimental conditions, monitoring the $e^+$ plasma radius with the mode analysis technique, we observe an expansion of roughly 0.1 mm in the first 10 s and of $\simeq 0.25$ mm in the full cycle of 180 s. It should be noted that this expansion does not significantly affect the space charge potential of the $e^+$ plasma.

To show that the slow cooling takes place on the initial radially separated antiprotons, dedicated measurement have been performed. The $e^+$ plasma shape was altered by applying a rotating wall electric field and the antiprotons were dumped 10 ms after injection. The rotating wall was used both in expansion and compression mode. The results shows that when the $e^+$ plasma is expanded (aspect ratio $\alpha \simeq 7$) about 40% of the population is in region I and 60% in region II. When the rotating wall is not applied ($\alpha \simeq 20$) 71% of the antiprotons are in region I and only 29% in region II. By compressing the plasma ($\alpha \simeq 80$) 83% of the antiprotons are in region I and 17% in region II.

We also note that, for long interaction times, there is a growth of the $\bar{p}$ population in region II (see Fig. 23). The energy separation between the zero energy level...
and this part of the population is 5–6 eV. This is compatible (within the experimental accuracy of \( \simeq 2 \) V) with the 4 V that separates the potential on axis with the one at a radius of \( \simeq 3 \) mm (see Fig. 22(b)), indicating a possible slow feeding of antiprotons to the \( e^+ \) plasma. It is also important to note that in Fig. 23 the position of the population peak of the region III (right well) remains stable during the whole process.

8.4. Temperature dependence

As previously stated, the two antihydrogen production mechanisms of Eqs. (3) and (4) have different dependence on the positron plasma temperature. Important insights into the formation mechanism and state distribution could therefore be obtained by studying the temperature dependence of the production of antihydrogen. Such dependence is studied in ATHENA thanks to the plasma mode diagnostics and to the capability to change the positron plasma temperature applying a specific excitation near the dipole frequency to one of the trap electrodes (see Sec. 7). The antihydrogen production temperature dependence has been extracted in two different ways: (1) measuring the production rate as a function of the positron plasma characteristics;\(^{81}\) (2) studying the antihydrogen production rise time in “heat ON/heat OFF” cycles inside the same mixing sequence.\(^{80}\) In the following a description of the applied techniques and the corresponding results are presented.

8.4.1. Production rate as a function of the positron plasma

For this measurement the positron plasma is characterized by a typical length of 32 mm, radius of 2.5 mm, particle number \( 7 \times 10^7 \), density \( 1.7 \times 10^8 \) cm\(^{-3} \) and storage time of thousands of seconds. The reproducibility of the results, over several weeks and under different conditions, was good. Maximum variations in density of about 30% were observed.

During mixing the positron plasma temperature could be changed and monitored in a controlled way as described in Sec. 7. The minimum measurable temperature increase is about 15 meV (\( \simeq 175 \) K). Note that the mode diagnostic yields only relative temperature changes and not the absolute temperature of the positron plasma. The electrode temperature of 15 K is thus the lower limit for the unheated plasma temperature, and we adopt this as our unperturbed temperature.

Mixing of positrons and antiprotons is carried out for different positron plasma temperatures (Table 2). Four samples contain enough data to allow a detailed analysis of antihydrogen production, as described in Ref. 1. This set includes the cold mixing where no heating was applied, as well as three samples with \( \Delta T = 15 \pm 15 \) meV (\( \simeq 175 \) K), \( \Delta T = 43 \pm 17 \) meV (\( \simeq 500 \) K) and \( \Delta T = 306 \pm 30 \) meV (\( \simeq 3500 \) K, hot mixing sample).

For the two samples in Table 2 with a temperature increase lower than our resolution of 15 meV, a linear correlation between the applied heating voltage and the temperature increase is assumed. A quadratic behavior, possible in this regime
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Table 2. Summary of the results of measurements with different positron plasma temperatures. $\Delta T$ is the temperature increase. "$\bar{p}$'s" is the total number of antiprotons used in the mixing cycles. The "cos $\vartheta_{\gamma\gamma}$ excess" is the opening angle excess and "peak" is the peak trigger rate (see text for details). These quantities are available only for the high statistics samples. The integrated number of triggers for different time intervals from the start of mixing cycle are also reported. All the values are normalized to a standard cycle with $10^4 \bar{p}$'s. The errors in $\Delta T$ represent the maximum systematic uncertainty. The errors in cos $\vartheta_{\gamma\gamma}$, peak trigger rate, and number of triggers are each the combination of statistical and systematic errors.

<table>
<thead>
<tr>
<th>$\Delta T$ (meV)</th>
<th>$\bar{p}$'s $\times 10^6$</th>
<th>cos($\vartheta_{\gamma\gamma}$) excess</th>
<th>Peak (Hz)</th>
<th>Triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(294 ± 21)</td>
<td>1.65 ± 0.19</td>
<td>454 ± 44</td>
<td>441 ± 40</td>
</tr>
<tr>
<td>3$^{+15}_{-7}$</td>
<td>(3.46 ± 0.25)</td>
<td>—</td>
<td>—</td>
<td>395 ± 38</td>
</tr>
<tr>
<td>15 ± 15</td>
<td>(182 ± 13)</td>
<td>1.08 ± 0.15</td>
<td>381 ± 38</td>
<td>352 ± 32</td>
</tr>
<tr>
<td>25 ± 15</td>
<td>(3.13 ± 0.22)</td>
<td>—</td>
<td>—</td>
<td>214 ± 22</td>
</tr>
<tr>
<td>43 ± 17</td>
<td>(152 ± 11)</td>
<td>0.65 ± 0.11</td>
<td>140 ± 16</td>
<td>167 ± 15</td>
</tr>
<tr>
<td>121 ± 19</td>
<td>(3.22 ± 0.23)</td>
<td>—</td>
<td>—</td>
<td>73 ± 8</td>
</tr>
<tr>
<td>306 ± 30</td>
<td>(106 ± 8)</td>
<td>0.04 ± 0.01</td>
<td>22 ± 5</td>
<td>33 ± 3</td>
</tr>
</tbody>
</table>

of low heating power, would result in very similar $\Delta T$'s, the differences being well within the uncertainties associated to these temperatures.

To measure the production of antihydrogen, as described in detail in the following, various variables are considered: the “opening angle excess,” the “peak trigger rate” and the total number of triggers in the mixing cycle. The first two are available only in the four sample at high statistics, while the last one can be used in all the temperature samples.

For clarification it should be stressed that in the following $\bar{H}$ production refers only to detected antiatoms that annihilate on the walls of the charged particle trap within the detector volume. The detector solid angle coverage for $\bar{H}$ emerging isotropically from the trap center and annihilating at the electrodes is estimated to be $\sim 98\%$ by MC calculation. Due to the complicated nested trap dynamics, this number is different from the number of antiatoms that are effectively formed during the $\bar{p} - e^+$ interaction.$^{76,78,82}$

As previously discussed, the opening angle distribution and especially the peak at cos $\vartheta_{\gamma\gamma} = -1$ are clear signs of antihydrogen production. For this reason, the “opening angle excess,” defined as the number of events with cos $\vartheta_{\gamma\gamma} \leq -0.95$ exceeding the central plateau (see Table 2), is shown as a function of the temperature in Fig. 26(a). This number is proportional to the total number of $\bar{H}$ atoms produced during a standard cycle.

We have shown previously (Subsec. 8.2) that in cold mixing the antihydrogen annihilations account for a significant fraction ($\sim 65\%$) of the trigger rate. In Table 2 the number of triggers in the time windows 0–3 s and 0–180 s, where 0 is the start of mixing and 180 s is the maximum mixing interval are reported. These values
Fig. 26. Temperature dependence of \( \bar{H} \) production using different variables. All the quantities are normalized to the cold mixing sample. They are displayed as a function of the absolute positron plasma temperature assuming a cold mixing temperature of 15 K. (a) Opening angle excess for the high statistics samples; (b) number of triggers for all the samples (the hot mixing sample is used as background, thus it is not shown); (c) peak trigger rate for the high statistics samples.

Figure from Ref. 81.

are corrected for the trigger efficiency. The total number of triggers during mixing as a function of the positron plasma temperature is shown, for all the samples, in Fig. 26(b). The hot mixing data are interpreted as the background due to \( \bar{p} \)-only annihilations and are subtracted from the other samples. The temperature dependence of the trigger data is very similar to that of the opening angle excess. This suggests that the integrated number of triggers, after hot mixing background subtraction, is a good proxy for antihydrogen formation not only in cold mixing, as previously shown in Subsec. 8.2, but also in the heated samples described here.

We have also looked at the “peak trigger rate” defined as the maximum value of the detector trigger rate after the start of mixing, excluding the first 20 ms when some \( \bar{p} \)'s can be lost immediately upon the injection into the nested trap. Note that,
for the samples where antihydrogen production is present, a dramatic increase in the rate of annihilations is observed when antiprotons are injected into the positron plasma. The peak trigger rate as a function of the plasma temperature is shown in Fig. 26(c) and the values, corrected for the trigger efficiency, are reported in Table 2. We have previously shown (Subsec. 8.2) that integrated over the first second of mixing, more than 85% of the triggers are due to $\bar{H}$ production. We expect this percentage to be even higher for the peak trigger rate. If we use the _hot mixing_ as a background (see Table 2) we can estimate this fraction to be around 95%, corresponding to an absolute instantaneous $\bar{H}$ rate of $432 \pm 44$ Hz.

It is here important to note that the three curves in Fig. 26 contain slightly different information. The opening angle excess is a definitive measurement of the total integrated antihydrogen production for the 180 s mixing cycle. The same is true for the total number of triggers after background subtraction. Both of these integrated plots are sensitive to effects such as spatial decoupling of the two particle clouds, and in that sense cannot be used as indications of instantaneous combination rate. On the contrary, the peak trigger rate is a “cleaner” measurement of the combination rate at the beginning of the mixing cycle, after the prompt cooling, when we believe that the inner core of the $\bar{p}$ distribution is closest to thermal equilibrium with the positrons (see Subsec. 8.3).

We thus examine the peak trigger rates in Fig. 26(c) for compatibility with the predictions for the two production mechanisms. Several general features are evident. First, the antihydrogen production is observed to decrease with increased positron plasma temperature, as expected. It is also interesting to note that antihydrogen is clearly present even for room temperature positrons.

The second main feature is that the $\bar{H}$ formation does not scale as a simple power law with the $e^+$ temperature. There is a clear turnover of the rate at low temperature. Furthermore, all attempts to fit the data with combinations of power laws, e.g. representing a mixture of two and three-body processes, are unsuccessful. The presence of the latter is expected to be most pronounced at temperatures below $\sim 10$ meV ($\simeq 100$ K). The lower temperature data are however characterized by a leveling-off, rather than an increase. The naive scaling for TBR, $T^{-9/2}$, is clearly inconsistent with our data. It should be noted that collisional relaxation and finite transit time of the antiprotons through the positron plasma can lead to a different temperature scaling for TBR.\(^{78,84,85}\) Even though a simple power law is not able to fully reproduce the behavior of our data, a best-fit power law to the peak trigger rate curve (Fig. 26(c)) yields a dependence of $T^{-0.7 \pm 0.2}$ (compared to $T^{-0.63}$ in Ref. 84). The agreement with the radiative reaction seems reasonable, at least as far as the scaling with temperature is concerned, but when an estimate of the production rate is calculated it comes out to be at least an order of magnitude lower with respect to the measured rates of Table 2.\(^{81}\)

It is important here to note that it is difficult to correlate the experimental temperature behavior to the model predictions, since the dynamics of the $\bar{H}$ formation and transport to the walls is intricate.\(^{76,78,82}\) Indeed, the detectable antihydrogen
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flux is determined by the competition of the formation/decay chain with the ionization processes. For example, the antiatoms formed must pass the combined fields of the positron plasma and the nested trap without being ionized. This interplay could also be at the origin of the turnover in the production rate at low temperature, that is difficult to explain in other ways since all the models predicts higher production at lower temperature. A dedicated simulation\textsuperscript{78} shows that doubling the temperature, from 15 K to 30 K, decreases the $\bar{H}$ fraction by a factor 2.6 instead of a factor of 23. The crucial point in the simulation is whether the binding energy is sufficient to allow the $\bar{H}$ to survive to collisions and to field ionization and to reach the trap walls. Therefore, the global behavior with temperature is not sufficient by itself to determine the role of the two and three-body formation in the ATHENA nested trap.

These points will be further discussed in Subsec. 8.5.

8.4.2. Production rise time in “heat ON/heat OFF” cycles

The heating procedure that has been used to change the temperature was also applied intermittently during the mixing cycle to turn on and off the antihydrogen production, demonstrating a temporally controlled production of $\bar{H}$.\textsuperscript{80} Our observations establish a pulsed source of cold $\bar{H}$ atoms, with a rise time of about 1 s and pulse lengths ranging from 3 s to 100 s.

Figure 27(a) displays the time and axial position distributions of $\bar{p}$ annihilation vertices in which the RF is applied with a square wave modulation with a 15 s off-15 s on cycle. In Fig. 27(b) the RF modulation is applied with the opposite phase. In both cases, the annihilation events are dramatically suppressed, within a time $\leq 100$ ms after the RF is turned on. The annihilations recover within a few seconds once the RF is turned off, as the $e^+$ temperature return to base (see below). The RF-off vertex position distributions (see Fig. 27, lower panel) are consistent with $\bar{H}$ production, while those for RF-on suggest annihilations dominantly on residual gas, or possibly trapped ions (see Sec. 9). The presence of the peak at $\cos\theta_{\gamma\gamma} \approx -1$ in the opening angle distribution of 511 keV $\gamma$ rays in the absence of the heating RF demonstrates unambiguously the $\bar{H}$ production with modulation periods ranging from 3 to 100 s.\textsuperscript{80}

In order to understand the temporal behavior of the $\bar{H}$ modulation, we consider a simple model as follows: turning on the RF heats the $e^+$ plasma by $\Delta T$, immediately suppressing $\bar{H}$ production. When the RF is turned off, the $e^+$ plasma self-cools to the equilibrium temperature $T(0)$ via emission of synchrotron radiation with a time constant, obtained from the analysis of these data, $\tau_e = 0.48 \pm 0.05$ s (see also Fig. 28). A possible systematic shift of $\tau_e$ with the heating amplitude is included in the uncertainty. The $\bar{H}$ formation recovering follows a similar time constant. If the temperature evolution of the $e^+$ plasma is known, then the temperature dependence of $\bar{H}$ formation can be deduced, which in turn provides information on $\bar{H}$ formation dynamics in a nested trap. We quantitatively test this model, focusing on the onset of antihydrogen production upon turning the heating off.
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Fig. 27. Spatial and temporal distributions of $\bar{p}$ annihilations during the modulated RF heating of the $e^+$ plasma, illustrating modulated $\bar{H}$ production. (a) Heat on–off, and (b) off–on cycles. In the upper panels the heat off period is shaded. Figures from Ref. 80.

We recall also that the $e^+$ cooling time at $B = 3$ T can be calculated from Ref. 86 as $\tau_{e} = 0.43$ s.$^{80}$

We now present a series of $\bar{H}$ modulation data, with an RF modulation cycle of 5 s off-3 s on. Seven periods of the on-to-off transition occurring during the 70 s mixing time are summed over typically 10 mixing cycles for each initial temperature, such that about 70 transitions per data set are used for the analysis. We consider here the annihilation rate from the detector trigger signal, rather than the reconstructed vertex rate. The former has negligible dead time compared to the latter (at the cost of having no position information), and hence can provide more accurate time information. In Fig. 28 annihilation time distributions are shown for (a) $\Delta T = 870$ meV (error bars), and (b) 270, 400, 870, 1150 and 1470 meV (histograms).

In order to fit these data, a temperature power scaling of the production rate, i.e. $R_{\bar{H}}(T) \propto T^{-P}$, is assumed, where $T$ is the $e^+$ temperature. Assuming that the disappearance of the $\bar{p}$ is dominated by $\bar{H}$ production over the timescale of interest ($< a$ few seconds), the observed $\bar{p}$ annihilation rate $\lambda(t)$ can be written as:

$$\lambda(t) = A \left[ \Delta T \exp \left( -\frac{t}{\tau_e} \right) + T_0 \right]^{-P} + B_k,$$  \hspace{1cm} (12)
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Fig. 28. (Color online) Onset of the $\bar{H}$ production upon heat off at $t = 0$. (a) The data with $\Delta T = 870$ meV (error bars). Green curve: the $e^+$ temperature evolution with $\tau_e = 0.48$ s. Red curve: a representative fit giving $\propto T^{-1.2}$. Dashed red curve: exponential fit. Blue: the case with $R_{\bar{H}} \propto T^{-4.5}$. (b) The data and representative fits for different $\Delta T$. Fit time windows (indicated by solid curves) were set with $T_{\text{low}} = 1$ meV (see text). The data sets (which are vertically displaced for clarity) were taken with between $0.7-1.6 \times 10^5 \bar{p}$. Figures from Ref. 80.

for $t > 0$ and $\lambda(t) = A[\Delta T + T_0]^{-P} + B_k$ for $t < 0$. $T_0$ (base temperature), $A$ (normalization) and $B_k$ (background), as well as $P$, are the fit parameters. In this model, in the limit of $T_0 \to 0$ and no background, the slope of the onset of $\bar{H}$ production in a logarithmic plot represents the power scaling $P$. Our data show indications of such scaling, especially at intermediate time where the effects of $T_0$ and $B_k$ are small.

Increasing $\Delta T$ results in delayed onset of $\bar{H}$ production as expected, since it takes longer for the $e^+$ plasma to cool down. Representative fits are illustrated by the curves in Fig. 28. The red curve in (a) is a fit to the $\Delta T = 870$ meV data, resulting in the scaling $P = 1.2 \pm 0.2$, and an effective base temperature of $T_0 = 180 \pm 50$ K, where the errors are statistical only. The green curve shows...
the $e^+$ temperature evolution, where $T_0$ is taken from the fit above. The blue curve is the case where the conventional TBR scaling $P = 4.5$ is assumed. Here the onset of the $\bar{H}$ production would be much delayed, a scenario which is clearly incompatible with the data. Similar fits to the data with different $\Delta T$ are given in curves in Fig. 28(b). The fit time windows (indicated with solid curves) were taken to be $-2 < t < (\tau_\text{e} \ln(\Delta T = T_{\text{low}}))$ s, where the effective low temperature cutoff $T_{\text{low}}$ is set to 1 meV here. We observe that the fitted base temperatures $T_0$ obtained are typically higher than the nominal trap temperature of 15 K. In our model of Eq. (12), deviation from power scaling at low temperatures as implied in the previous section, would be accounted for by a higher value of $T_0$. In order to avoid the influence of the possible nonpower scaling at low temperatures, we make alternative fits, limited to the high temperature region, assuming the form: $\lambda(t) = A(\Delta T \exp(-t/\tau_\text{e}))^{-P} + B_k$, for $t > 0$. An example of such fit is depicted as “Exp fit” in Fig. 28(a), giving $P = 0.8 \pm 0.2$ with $T_{\text{low}} = 35$ meV.

Given the simplicity of our model, the overall agreement with the data is very good. We have carefully investigated systematic uncertainties by performing a number of fits by varying, e.g. $\tau_\text{e}$ and $T_{\text{low}}$. The exponential fits tend to give slightly lower $P$ than the standard fits. Taking into account these systematic effects, we obtain the scaling parameter of $P = 1.1 \pm 0.5$, i.e. $R_{\bar{H}} \propto T^{-1.1 \pm 0.5}$. The result is consistent with the results reported in Subsec. 8.4.1, but the present analysis substantially extends the measurements in the 100 meV to 1.5 eV range, and provides evidence for the power law behavior at these temperatures.

Since the full range of the temperatures is probed during a single pulsing cycle, the present method should be less sensitive to some of the possible systematics, such as normalization errors. However, our determination of $P$ is highly correlated with $\tau_\text{e}$, and hence relies on the validity of the plasma model used to extract it.

The results of this experiment are consistent with those of Subsec. 8.4.1: an interpretation of the data in the light of a simple power law is not realistic and thus a direct and clear indication of which production mechanism is the responsible in ATHENA for the antihydrogen production cannot be directly inferred.

A more detailed discussion will be presented in the following section.

8.5. Discussion on the production mechanisms

In attempting to unravel the SRR and TBR contributions of Eqs. (3) and (4) to the antihydrogen signal, we have evaluated antihydrogen detection rates utilizing triggers and the reconstructed vertex data. We have also used the resolving power of the detector to perform cuts to the data to isolate the vertices according to their radial and axial positions. Further insight on the recombination dynamics in the nested trap has also been gained from the temperature analysis of Subsec. 8.4, where a prompt production rate in agreement with TBR (see Table 2), but a temperature dependence difficult to be attributed to one mechanism or to the other have been found.
Here, by collecting all the information of the preceding sections, we attempt to formulate a plausible model of $\bar{H}$ formation in the ATHENA mixing trap.

In Fig. 29 we have fitted the behavior with time of the 2003 vertex data with the sum of two exponentials. The curve at longer times is described rather well by the second exponential, whereas the fit in the first seconds is only acceptable ($\chi^2/\text{Dof} = 2.87$). These cold mixing data refer to an average positron plasma density $n_e \simeq 6 \times 10^8 \text{ cm}^{-1}$. The two rates are:

$$\lambda_1 \simeq 0.139 \pm 0.006 \text{ s}^{-1}, \quad \lambda_2 \simeq 0.025 \pm 0.001 \text{ s}^{-1},$$

that are respectively in agreement, at least as the order of magnitude, with the rates $\lambda_d(\text{TBR})$ and $\lambda_d(\text{SRR})$ of Eq. (11) expected for TBR and SRR, respectively. We note that detailed analysis of the temporal behavior of the $\bar{H}$ signal revealed formation rates approaching those from the simulations.\textsuperscript{76}

It is also important to note that our data are mostly taken under conditions in which the $\bar{p}$ cloud is larger than the positron plasma, such that the slowing down and formation of $\bar{H}$ of those $\bar{p}$ in peripheral contact with the $e^+$ cloud will be retarded.

Therefore, the injection of $\bar{p}$ into the $e^+$ cloud should lead to the formation of nonthermal $\bar{H}$ with high axial speeds. These effects have been observed by ATHENA,\textsuperscript{87} since the distribution of $\bar{H}$ emerging from the formation region appears independent of the $e^+$ temperature and enhanced in the axial direction. The model reported in Fig. 30 assumes homogeneous formation throughout the $e^+$ plasma, and rotation of the $\bar{p}$ with the $e^+$. We argue that $\bar{H}$ is not formed under conditions

\[ \tau_1 = 7.2 \pm 0.3 \text{ s}; \quad \tau_2 = 40.0 \pm 1.2 \text{ s} \]
Fig. 30. (a) Axial $\bar{H}$ distributions for cold mixing and mixing with $e^+$ heated by two different temperatures indicated in the figure. The dot–dashed line is a simple calculation of isotropic emission from the $e^+$ plasma volume. The distributions are normalized to the same area. (b) Comparison of the $\bar{H}$ axial distribution from cold mixing with a number of calculated distributions. Standard $e^+$ plasma parameters are used except for the dot–dashed curve where an unrealistic plasma length $l_e = 6$ cm is assumed. Homogeneous $\bar{H}$ formation in the plasma is assumed. Figure from Ref. 87.

of complete thermal equilibrium between the $e^+$ and the $\bar{p}$. The lower limit values of the formation temperature are $T_p^\parallel = 150$ K and $T_p^\perp = 15$ K for the parallel and transverse components, respectively.

Therefore, a possible picture emerging from the ATHENA data discussed above, supported also by dedicated simulations,$^{76,78,82}$ of the manner in which antiprotons behave in positron plasmas in the density and temperature regime employed by ATHENA, is as follows. The rate of formation of weakly-bound $\bar{H}$ via the TBR, whilst the antiprotons reside in the positron plasma, is typically much higher than the equilibrium detection rate. This is because almost all of these antiatoms are reionized by positron impact, since this process will proceed with geometrical cross-sections $\sim 10^{-13}$ m$^2$, resulting in rates in excess of $10^5$ s$^{-1}$, even at our lowest value of $e^+$ density. Thus, the nascent $\bar{H}$ atoms are almost always destroyed on collision.
Only those that survive the plasma electric field and further collisions with positrons can leave the plasma, so that events involving pairs sufficiently deeply bound to eventually annihilate on the electrode walls are comparatively rare. Therefore, the consequences for the $\bar{H}$ atoms leaving the plasma depend strongly upon the binding energy of the pair, but many weakly-bound $\bar{H}$ atoms are stripped as they leave the positron cloud. Following this picture, the field ionized antiprotons which become trapped derive from $\bar{H}$ atoms formed close to the edge of the plasma. These precursor $\bar{H}$ atoms have typically traveled a very short distance inside the plasma, in contrast to those which escape the plasma and are detected, which are formed much more uniformly throughout the plasma. In Subsec. 8.2 we reported an estimated $\bar{H}$ production efficiency of $(17 \pm 2)\%^{36,77}$ per injected $\bar{p}$, in comparison with a percentage of 33% coming from a simulation based on TBR and on the mechanisms discussed above.\textsuperscript{78}

When bound to a positron, the $\bar{p}$ can cross the magnetic field lines to which they are otherwise tightly pinned. Thus, the recombination-plus-reionization cycles transport the $\bar{p}$ across the field lines, towards the outskirts of the plasma. This effect, suggested also by the simulations\textsuperscript{76,78,82} could explain the ATHENA observations on the long term $\bar{p}$ dynamics in the mixing trap reported in Subsec. 8.1. A similar effect has also been discussed recently by the Antihydrogen Laser PHysics Apparatus (ALPHA) antihydrogen trapping collaboration.\textsuperscript{88}

At the edge of the plasma the $\bar{p}$ inhabit a region where the nascent $\bar{H}$ atoms formed by TBR cannot become more tightly bound by further collisions with $e^+$ (as can occur when they are formed in the body of the positron plasma) such that a continuous formation and reionization cycle ensues. Thus, $\bar{H}$ formation by SRR is favored. The resulting antatomic states will be much more strongly bound than for TBR. Following this picture, we ascribe the events at short time to TBR, whilst later in the mixing cycle we think that $\bar{H}$ production via SRR is the main mechanism.

At our present densities, the incomplete overlap of $\bar{p}$ and $e^+$ clouds at the beginning of the mixing, together with the radial transport of the $\bar{p}$ to the plasma edge via repeated $\bar{H}$ formation and reionization cycles, means that, at a certain time in the mixing cycle which is dependent upon the $e^+$ density (via the rate of the TBR), the interaction of peripheral $\bar{p}$ with the $e^+$ dominates the experimental observations. A major outcome of the above is that the timescales for $\bar{H}$ production will become longer than predicted from theories based upon steady-state equilibrium interaction and will extend across the entire mixing cycle.

8.6. Laser-induced formation of $\bar{H}$

In addition to the spontaneous recombination processes detailed in the previous section, antihydrogen formation can also be accomplished by laser-stimulated recombination (LSR), according to the reaction

\[ e^+ + \bar{p} + h\nu \rightarrow \bar{H} + 2h\nu. \] (14)
It was first suggested as a possible mechanism for positronium formation and later proposed as an alternative technique for antihydrogen production.\textsuperscript{72,83} In addition to enhancing the total spontaneous $\bar{\text{H}}$ formation rate, this process is attractive because it affords a selectivity of the populated quantum state and allows a time-resolved production in case a pulsed (or chopped) laser is employed. LSR has been used to enhance the recombination of hydrogen into a wide range of quantum levels in merged-beam experiments with protons and electrons.\textsuperscript{89,90} In the latter, an enhancement of hydrogen recombination by a factor 4 was observed with a 15-W CO\textsubscript{2} laser.

In thermal equilibrium, the partial laser-mediated recombination rate into a bound state with principal and angular momentum quantum numbers ($n, l$) is given by\textsuperscript{83}

$$R_{nl}^{\text{nl}} = N_p N(E) w_{nl} \frac{r_{nl}^{\text{nl}}(E) \gamma_{nl}}{r_{nl}^{\text{nl}}(E) + \gamma_{nl}},$$

(15)

where $E$ is the electron energy, $N(E)$ is the level population function of the continuum Coulomb state, $w_{nl}$ is the statistical weight of the bound state, $N_p$ is the number of protons, $r_{nl}^{\text{nl}}$ is the induced absorption rate, and $\gamma_{nl}$ is the spontaneous radiative decay rate of the ($n, l$) state. In calculating the total recombination rate, one must sum over all possible final states, taking into account the Doppler width and the laser bandwidth, as well as the Zeeman splitting of the atomic levels in an external magnetic field. It follows from Eq. (15) that large rates are achieved with high power densities and small photon energies (i.e. when high Rydberg states are populated). Therefore, a multistep process in which a highly excited state is initially populated will be advantageous in terms of the required laser power.\textsuperscript{83} The 11d state was chosen primarily because high power CO\textsubscript{2} gas lasers in the relevant infrared wavelength range at $\lambda \simeq 11$ $\mu$m are commercially available. For the same reason, the driven transition into the 11d state was also chosen as a test case for laser-stimulated antihydrogen with ATHENA. However, for reasons of simplicity only the first stimulated recombination step was carried out, relying on spontaneous radiative decay for the further de-excitation to the ground state.

The ATHENA apparatus was slightly modified\textsuperscript{91} to allow access of the laser beam (diameter 2 mm) to the mixing region and to bring it into overlap with the $e^+$ plasma (diameter 1 mm). The path of the laser beam was mechanically well constrained by diaphragms at the laser windows and the large distance from the diaphragms to the interaction region, given by the mechanical size of the superconducting magnet. The tunable CO\textsubscript{2} laser operated at a wavelength of $\lambda = 10.96$ $\mu$m and supplied a power of 10 W and a peak intensity of $I \simeq 160$ W/cm. Its bandwidth was $\Gamma_{\text{las}} \simeq 100$ MHz. For the ATHENA experimental conditions (and assuming thermal equilibrium at $T_0 = 15$ K), Eq. (15) yields a total stimulated $\bar{\text{H}}$ production rate of 60 Hz, whereas the spontaneous radiative rate was estimated at 24 Hz; hence, a sizable enhancement factor of roughly 3.5 was expected. However, as discussed at the beginning of this section, the collisional recombination rates
should be much higher, at least partially masking the enhancement effect. Since
the intermediate \(2p\) state was not depleted by stimulated emission, its reionization
while the \(\bar{H}\) atom is still within the laser beam must also be considered. Furthermore, the highly excited states formed by TBR are also subject to reionization by
the 11 \(\mu\)m laser. It was calculated, however, that the radiative decay rate exceeded
the reionization rate for all states with principal quantum number 11 < \(n\) < 60,
with ionization probabilities generally below 60%. A comparison of laser ON and
OFF events was achieved by pulsing the laser light with a chopper at a frequency
of 25 Hz and recording the state of the laser along with each annihilation event.

The antihydrogen production was performed by standard cold mixing, and a
total of 156,000 annihilation events were recorded during 345 mixing cycles of 50 s
each. To determine the impact of laser stimulation on antihydrogen formation,
the following parameters were studied: (1) the time evolution of the event rate;
(2) the spatial (2D or radial) \(\bar{p}\) annihilation vertex distribution; (3) the opening
angle distribution of 511 keV photon events in coincidence with the \(\bar{p}\) annihilation
events, as in Figs. 9 and 24. The latter two parameters are shown in Fig. 31. In order
to suppress background events, which mainly originate at the trap center, radial
cuts limiting the active region to 0.7 < \(R\) < 2.5 cm were applied, as indicated in
the figure. The data display no significant deviations between the laser ON/OFF
signals. This observation also holds when different time subintervals during the
mixing cycle are considered. These measurements therefore yielded a clear null
result (apart from a sharper \(\cos \theta_{\gamma\gamma} = -1\) peak present in all the laser data),
which suggests that radiative recombination makes a negligible contribution to \(\bar{H}\)
formation under the experimental conditions of the ATHENA apparatus.

The two sets of experimental results presented in this section strongly indi-
cate that the theoretical models that describe antihydrogen formation in thermal
equilibrium and in the presence of external electric and magnetic fields cannot
adequately describe the more complex situation of $\bar{\text{H}}$ production with the nested-trap technique. In addition to the influence by the external fields, also a modified temperature scaling due to collisional relaxation and finite transit time of the anti-protons through the positron plasma must be considered.

We conclude that the prevalence of TBR and the laser ionization of the high-$n$ Rydberg states formed in this way could mask a small contribution from laser induced radiative recombination.

9. Protonium Production

After the confirmation of the antihydrogen production, a more detailed analysis of the data collected with the ATHENA apparatus showed that also protonium (Pn) was simultaneously produced.\textsuperscript{92–95}

Protonium (also called antiprotonic hydrogen) is the quasi-stable proton–antiproton bound state. Its main features can be understood from the simple Bohr formula.

When protonium is in a state with low quantum numbers ($n, l$), the proton and the antiproton are very close and the strong interaction can be studied. Indeed this was the major interest for studying protonium since its discovery.

On the contrary, when protonium is in high ($n, l$) states, it is a very simple system and its energy levels can be easily calculated with high precision. The Bohr formula indicates that the protonium transition energies, depending on the reduced mass of the system, are approximately increased by the ratio $m/m_e$ of the mass of the captured antiproton and of that of the electron in respect to the transition energies of the hydrogen atom.

Although Pn has been extensively studied in the past, this has been performed only by stopping antiprotons in liquid or gaseous targets for X-ray spectroscopy of inner shell cascades or for studying $\bar{\text{p}}\text{p}$ annihilations at rest (see e.g. Refs. 96 and 97). The production method achieved in ATHENA is radically new, because it occurs in vacuum with the formed Pn atoms having very low kinetic energy (from some meV to $\sim$ 1 eV). Precision spectroscopy measurements could be performed to determine the so-called antiprotonic Rydberg constant and/or the $\bar{p}/e^-$ mass ratio, in a similar way as achieved with antiprotonic helium ($\bar{p}\text{He}^+$) by the ASACUSA Collaboration.

9.1. Experimental results and interpretation

The identification of the protonium signal essentially relies on the detector capability to determine the $\bar{p}$ annihilation position and to identify the signal produced by the two back-to-back 511 keV photons produced by the $e^+$ simultaneous annihilation, occurring only when the antihydrogen annihilates. To be more precise, in typical operating conditions, annihilation of $\bar{p}$’s originate from:

(i) $\bar{\text{H}}$ formation followed by annihilation on the electrode surface;\textsuperscript{1,87}
(ii) $\bar{p}$ annihilation in some well-defined “spots” on the electrode walls due to radial transport;\textsuperscript{41}

(iii) annihilation following interactions with residual gas atoms or ions present in the trap.

While the annihilations of the first type are the only ones showing the already mentioned signal produced by the two back-to-back 511 keV photons, the annihilations belonging to the second type can be easily identified because of the absence of this signal and of their strong spatial localization. The present section concerns the annihilations of the third group, which were demonstrated to come mainly from protonium formed near the center of the trap and annihilating after a short travel toward the trap electrodes (but without reaching them at usual operating conditions, and reaching them in a fractional amount when working at the highest temperature achieved in the ATHENA apparatus).

In this respect, it is interesting to notice that, during the manipulation of the positrons for antihydrogen production, several thousands of ions are trapped alongside the positrons, where they seem to reach a thermal equilibrium state. In a dedicated experiment, the time of flight of the detected ions permitted to exclude that they could be protons while it was compatible with ions of molecular hydrogen (more likely) or of helium. In addition through the measurement of the collected charge, the number of these ions is estimated to be around $10^4$–$10^5$ under typical ambient conditions.

It is shown in Ref. 77 that, during cold mixing, when the $e^+$ cloud is kept at the trap environment cryogenic temperature of $\sim 15$ K, most of the events are due to $\bar{H}$ annihilations even if some annihilations near the trap axis are present. Otherwise, during hot mixing, when the $e^+$ cloud is heated by a RF drive applied to an electrode of the trap\textsuperscript{40,70} to a temperature of several thousand K (8000–10,000 K for the data reported here), $\bar{H}$ formation is strongly suppressed\textsuperscript{81} and $\bar{p}$’s annihilate mainly without forming $\bar{H}$.

Figure 8 shows the $x$–$y$ distributions (both coordinates are in the plane perpendicular to the trap axis) of the annihilation vertices for the cold mixing (“Cold” in Fig. 8) and hot mixing data (“Hot” in Fig. 8), together with MC simulated data of the annihilations on the trap wall (“ghMC” in Fig. 8). In “Fit result” of Fig. 8, we report also the result of the superposition of the simulated annihilation on the trap wall with another distribution corresponding to annihilations near the trap center, the weight being set in order to reproduce at the best the real cold mixing data.

Therefore, even though all the distributions are broadened by the uncertainty in the vertex reconstruction, it is clear that two different structures are merged in the cold mixing case, while in the hot mixing just one is visible. For the cold mixing case, besides the annihilations on the trap wall situated at $r = 1.25$ cm due mainly to $\bar{H}$ (as shown in Ref. 77) and having a relatively wider $z$-distribution,\textsuperscript{87} there are some annihilations situated near the center of the trap and with a very sharp
z-distribution (see Fig. 32(a)). For hot mixing only the latter are present, with a tail that reaches the wall. In addition their axial distribution is much broader (see Fig. 32(b)) than for the cold mixing case.

The capability of the ATHENA apparatus to detect the spatial and temporal coincidence between \( \bar{p} \) and \( e^+ \) annihilations, and therefore to separate H from other annihilations, allows us to understand that for the hot mixing case almost all the annihilations (even those on the trap wall) are not due to \( \bar{H} \), while for the cold mixing case we have to distinguish between annihilations near the trap axis, that are not due to \( \bar{H} \) (apart from a few poorly reconstructed vertices), and on the trap wall, where the number of non-\( \bar{H} \) annihilations is negligible.

This can be inferred if we look at Fig. 10 where we draw the distribution of the cosine of the angle between the two detected photons, \( \cos \theta_{\gamma\gamma} \). We expect that this distribution should have a relatively sharp peak in \( \cos \theta_{\gamma\gamma} = -1 \) if annihilations are due to antihydrogen, because of the two back-to-back 511 keV photons produced by the \( e^+ \) annihilation, while we do not expect any peak for annihilations not related to \( \bar{H} \) (like in the protonium case). Figure 10(a) shows this distribution for the vertices selected near the trap wall for cold mixing data sample, while Fig. 10(b) refers to the same data sample but for the vertices near the trap axis: in the first case, there is a strong antihydrogen signal which is absent in the second case. On the other hand, Fig. 10(c) shows the same distribution for the hot mixing data sample, in which there is no observable peak in \( \cos \theta_{\gamma\gamma} = -1 \) related to the antihydrogen annihilations.

Further interesting information on the antiproton annihilation can be extracted by analyzing the number of the tracks coming from each annihilation vertex, corresponding essentially to the number of charged pions produced after annihilation, which depends in turn on the type of nucleon (proton or neutron) the \( \bar{p} \) annihilates with. Table 3 shows the ratios, \( R_{23} \), of the number of the reconstructed annihilation vertices having two tracks to those with three tracks, for different data samples. In order to have a better understanding of these data, a MC simulation of protonium annihilations inside the ATHENA apparatus has been performed and the result has
Table 3. Experimental and simulation results for the number of charged pion tracks due to $\bar{p}$ annihilations.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Ratio $R_{23}$ on wall</th>
<th>Ratio $R_{23}$ at center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold mixing</td>
<td>1.35 ± 0.01</td>
<td>1.22 ± 0.04</td>
</tr>
<tr>
<td>Hot mixing</td>
<td>1.38 ± 0.10</td>
<td>1.17 ± 0.04</td>
</tr>
<tr>
<td>$\bar{p}$’s only (no mixing)</td>
<td>1.40 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>Monte Carlo $\bar{p}p$</td>
<td>1.19 ± 0.01</td>
<td>1.19 ± 0.01</td>
</tr>
</tbody>
</table>

been reported on the last line. Comparing these data, we see that the annihilations on the wall differ from those originating inside the trap, which are compatible only with $\bar{p}p$ annihilations both for cold mixing and hot mixing.

Combining this information, we infer that the most probable $\bar{p}$-ion reaction is:

$$\bar{p} + H^+_2 \rightarrow P_n(n, l) + H,$$  \hspace{1cm} (16)

where protonium is produced with quantum numbers $n$ and $l$.

Assuming the reaction of Eq. (16), we have performed MC simulations in order to extract relevant information of the formed $P_n$ from the comparison with the experimental data.

Taking into account the geometrical values (radius $r_p = 1$ mm, length $z_p = 16$ mm) and the rotation frequency ($\omega = 300$ kHz) of the positrons cloud determined by the nondestructive method described in Refs. 40 and 70, the best fit of the simulations to the experimental data has been obtained with the following assumptions:

(i) for the cold mixing case, the $P_n$ are formed on the surface of the $e^+$ plasma ($r = r_p = 1$ mm) with a Gaussian distribution along the trap axis centered at the symmetry plane of the plasma with $\sigma = 2.5$ mm; for the hot mixing case the $\sigma$ value of the axial distribution is $10$ mm, thought limited to the plasma length, and the results are quite insensitive to the exact value of the initial radial position of the $P_n$ (i.e. $r$ can be in the range $0$–$1$ mm);

(ii) the $P_n$ velocity comes from the sum of the velocity $v_{\text{tang}}$ induced by the $E \times B$ plasma rotation as $v_{\text{tang}} = E \times B/|B|^2$ (where $E$ is the self-electric field of the $e^+$ plasma and $B$ the magnetic field) and of the isotropic thermal velocity $v_{\text{th}}$ given by a Maxwellian distribution. The corresponding mean radial kinetic energy of $P_n$ is about $40$ meV for cold mixing (dominated by $v_{\text{tang}}$) and $700$ meV in the hot mixing case (dominated by $v_{\text{th}}$).

(iii) the $P_n$ decay exponentially and the best fit corresponds to a mean lifetime of $(1.1 \pm 0.1)$ $\mu$s.

In Fig. 33 the result of the simulations and the experimental data are plotted for the cold mixing (a) and the hot mixing (b) case. For the experimental data of the cold mixing case, in order to subtract the $H$ contribution, we have considered the difference between the radial distribution taken in a $z$-slice where $P_n$ is present
Fig. 33. Experimental radial distribution (continuous line) of annihilations vertices with MC simulation (dashed line): (a) for cold mixing sample; (b) for hot mixing sample.

\(|z| < 0.5 \text{ cm}\) and the one where Pn is absent (e.g. \(0.5 < |z| < 1.5 \text{ cm}\)), normalized on the tail for \(r > 1.5 \text{ cm}\). The agreement is good both for cold mixing and for hot mixing data, where we have used the same lifetime as derived from the best fit to the hot mixing data and the Pn velocities are determined predominantly by the thermal and plasma environment. Thus Pn have been produced in a recoil-free collision and any attempt to reproduce the experimental data with Pn recoil energies of the order of 1 eV or higher fails.

9.2. Results in the absence of \(\text{H}_2^+\) ions

Further analysis on the results presented in Ref. 92 was discussed in Ref. 100. The radial and axial distributions of the protonium annihilations were examined in detail by considering also a particular set of data where the \(\text{H}_2^+\) ions were removed and the protonium signal was eliminated. This occurred with the so-called electrons-through-positrons (ETP) procedure that is a particular method to transfer electrons into the nested well arrangement by passing the electrons through the positron cloud.\(^{100}\)

This technique produces an expansion of the positron plasma and has been introduced in ATHENA to explore whether the \(\text{H}\) yield is limited by the number and the spatial dimensions of the positron plasma (with a density reduction to values in the range \(0.5–1.6 \times 10^8 \text{ cm}^{-3}\)), but it has also the effect to eliminate the positive ions at the trap center.

In Fig. 34, where the opening angle is plotted, a first clear difference between the different samples of data is shown. In the case of cold mixing and ETP samples the presence of the antihydrogen annihilations is clearly indicated by the peak in
the region of $\cos \theta_{\gamma\gamma} = -1$, while in the hot mixing case, as already discussed before, the absence of the peak suggests that the antihydrogen signal is strongly reduced and the annihilations events are predominantly due to the in-flight annihilations of protonium.

The inspection of the $\bar{p}$ annihilation vertices can be used to disentangle the protonium annihilations from the antihydrogen annihilations. Figure 35 shows the $r$–$z$ scatter plot for ETP, hot mixing and cold mixing samples where $r$ is the radial coordinate, i.e. the distance from the trap axis, while $z$ is the axial coordinate, i.e. the position along the trap axis. It must be noted that the vertex distributions are broadened by the detector resolution. The projections of the events on the $r$
Fig. 35. $r$–$z$ scatter plots for the annihilation vertices for the ETP (a), hot mixing (b) and cold mixing (c) data sets. Figure from Ref. 100.

axis are plotted in Fig. 36, broken down into the central ($|z| < 0.5$ cm) and lateral ($0.5 < |z| < 1.5$ cm) longitudinal regions. The events of the ETP case result to be centered on $r = 1.25$ cm, which corresponds to the radius of the trap. This is typical of antihydrogen annihilations considering also that the few events for small radius ($r < 0.5$ cm), see Fig. 35(a), indicates that the protonium events are absent.

The radial distribution of the ETP vertices is very similar to that obtained from a dedicated experiment where only antiprotons annihilations on the trap wall were present since the positrons were not injected into the trap.\cite{41} We deduce that also in this case the H$^+_2$ ions are missing.
Fig. 36. Radial distributions for the antiproton annihilation vertices for the ETP (a) and (d), hot mixing (b) and (e) and cold mixing (c) and (f) data sets. The plots (a), (b) and (c) are for the central axial vertex position $|z| < 0.5$ cm, while (d), (e) and (f) are for $0.5 < |z| < 1.5$ cm. The distributions in red are the MC simulations for antiproton annihilations on the trap wall fitted to the high radial values ($r > 1.25$ cm) of the experimental distributions. Figures from Ref. 100.

Also MC simulations of the antihydrogen annihilations on the trap wall reproduces very well the radial distributions, see Figs. 36(a) and 36(d). These simulated events, generated by means of the ATHENA MC program, are used to determine the fraction $F_c$ of the experimental events not annihilating on the trap wall for each data sample.

The parameter $F_c$ is computed as the relative difference between the counts of the experimental distribution and those of the MC distribution fitted to the higher radial portion ($r > 1.25$ cm) of the experimental data, see Fig. 36. In Table 4 the $F_c$ values are reported for three different axial regions: $|z| < 0.5$ cm and $0.5 < |z| < 1.5$ cm as in Figs. 36, and in a more external region ($2.5$ cm $< |z| < 3.5$ cm).

The ETP sample shows very low $F_c$ values (around 5%) in agreement with a signal mostly due to antihydrogen annihilation. The residual events at low radii could be due to a lack of accuracy in the MC simulations or to a small component of annihilations on the neutral residual gas inside the trap.

The hot mixing sample has the highest $F_c$ values (around 70%), which correspond to very large fractions of nonwall annihilations. This is consistent with events due to protonium annihilations while the antihydrogen signal, as expected,
is strongly reduced. For both ETP and hot mixing sample the parameter $F_c$ has a very low dependence on $z$, at least for the regions close to the positron plasma.

By contrast, the cold mixing sample presents a clear dependence of $F_c$ on $z$: for $|z| < 0.5$ cm the nonwall annihilations amount to 24%, while this fraction falls to 6–8% in the external regions. Therefore the central $z$ region contains a significant part of the protonium annihilations events.

The latter result provides a strong evidence that protonium in ATHENA is not formed through collisions with neutral molecular hydrogen ($H_2$). In effect in that case the signal would be present at low radii along a quite large $z$ range, including the Penning trap side wells placed around 3 cm far from $z = 0$. The strong localization of the protonium signals supports the firm belief that protonium in ATHENA is formed in interaction with $H_2^+$. 

The number of detected protonium annihilations in ATHENA is around 100 for every 60 s mixing cycle for both cold mixing and hot mixing working conditions. Taking into account a detector efficiency of around 50% and $10^4$ antiprotons per cycle, the protonium yield results to be about $2 \times 10^{-4}$ s$^{-1}$ per $\bar{p}$.

The cross-section of protonium production via the reaction of Eq. (16) has been calculated by Sakimoto$^{101}$ and by Cohen.$^{102}$ Their findings are similar and a comparison with the experimental yield can be pursued. The expected yields of protonium can be estimated for the hot mixing case, where, the $H_2^+$ ions should be distributed everywhere in the plasma, while in the cold mixing sample, where the ions are expected to form an equatorial belt around the center of the $e^+$ plasma, the evaluation is difficult. The different positioning comes from the different thermal energy. This can be explained if we consider that the combination of the self-electric field of the positrons plasma, $E$, and the axial magnetic field of the trap, $B$, produces a rotation of the positron plasma around the magnetic field lines. The same rotation is experienced also by the $H_2^+$ ions placed inside the $e^+$ plasma and, as a consequence of the different masses, the ions will be centrifugally separated from the positrons.$^{103-109}$ Actually the separation occurs only if the thermal energy is lower than a threshold temperature $T_{sep}$,$^{108,109}$ whose value for ATHENA is around 250–640 K in both hot mixing and cold mixing case. When the $e^+$ plasma temperature is below $T_{sep}$, like in the cold mixing case, the ions will move radially outside and longitudinally towards the center of the plasma where the electric potential has the lowest value.
For the hot mixing case, where the temperature of 10,000 K is much higher than $T_{\text{sep}}$, we can assume a uniform distribution of the $\text{H}_2^+$ ions inside the $e^+$ plasma, whose typical geometrical parameters are $z_p = 16$ mm and $r_p = 1$ mm. Considering $10^4$ ions, the $\text{H}_2^+$ density is around $1.5 \times 10^{11}$ m$^{-3}$. We can extrapolate the low energy trend of the Sakimoto’s cross-section $\sigma_{pp}$ for the reaction of Eq. (16) in order to get a result at 1 eV which corresponds to the ions energy at 10,000 K. The obtained value of $\sigma_{pp} \sim 8 \times 10^{-19}$ m$^2$ gives a protonium yield of $1.7 \times 10^{-3}$ s$^{-1}$ per $\bar{p}$, which is more than the experimental value. Indeed not all the antiprotons overlap the positron plasma such that the previous estimation can be considered overestimated. The agreement can be restored if we assume that the radial distribution of antiprotons is few mm while the $e^+$ plasma radius is 1 mm.

From the reaction of Eq. (16) it is possible to calculate the principal quantum number $n$ of the emitted $P_n$. The result is $n = 68$ if we assume no recoil for both the protonium and the hydrogen atom with the latter in its ground state and taking also into account that the binding energy of the $\text{H}_2^+$ in respect to dissociation into ($\text{H} + p$) is 2.6 eV. This result differs from the Sakimoto’s evaluation$^{101}$ which predicts $n = 34$ with a substantial $P_n$ recoil.

10. Discussion and Outlook

The success of ATHENA in 2002$^4$ with the production and detection of about $10^6$ atoms of $\bar{\text{H}}$, through the two and three-body reactions of Eqs. (3) and (4), was soon followed by another measurement from the ATRAP experiment.$^{25}$

The merging of slow $\bar{p}$ with a cold positrons plasma resulted in $\bar{\text{H}}$ atoms with a lower kinetic energy with respect to that of the antiatoms from the previous in flight experiments. The antiatoms produced by ATHENA could survive for longer times, of the order of $\sim 100$ µs before annihilating on the trap walls. This allowed ATHENA to obtain high $\bar{\text{H}}$ production rates and opened the door to the detailed studies illustrated in this paper.

10.1. Summary of the ATHENA results

The ATHENA main results can be summarized as:

(i) new techniques for $e^+$ trapping and cooling: a source of dense cryogenic plasma has been obtained$^{44}$ and new plasma control techniques for the $\bar{\text{H}}$ production have been tuned,$^{45}$ obtaining high values of the density by means of the rotating wall technique. New methods for the diagnostics of temperature and density of the positron plasma have been developed;$^{70}$

(ii) the optimization of the $\bar{p}$ trapping and cooling for $\bar{\text{H}}$ production, arriving to a standard transfer of $10^4 \bar{p}$ in the mixing trap.$^{27}$ New indications for sideband cooling of $\bar{p}$ in an electron gas, useful for future experiments with more intense $\bar{p}$ beams, are also given in Ref. 110;
the realization of a unique $\bar{\Lambda}$ annihilation detector, able to detect both $e^+$ and $\bar{\rho}$ annihilations in a precise space–time window. Thanks to the performances of this detector, the $\bar{\Lambda}$ annihilations have been for the first time disentangled from other processes and from the very complicated background, giving precious indications to many other experiments. The unique capability of antiparticle imaging has allowed, for the first time, the observation of the particle loss in a Penning trap and the detection of annihilation points localized in small “hot spots”; 

(iv) the study of $\bar{\Lambda}$ formation as a function of the positron plasma temperature and of the $\bar{\rho}$ cooling and dynamics in the nested trap. The high rate $\bar{\Lambda}$ production, obtained in this way, allowed the detailed comparison of the data of $\bar{\Lambda}$ production and detection with the predictions of dedicated MC models;

(v) the detection, for the first time, of protonium $p\bar{p}$ formation in a Penning trap. This aspect is important also as an indication of possible sources of background that could simulate the $\bar{\Lambda}$ annihilation, when the two back-to-back $\gamma$’s from positronium annihilations are not detected in coincidence with $\bar{\rho}$ annihilations.

These ATHENA achievements, including the emerging $\bar{\Lambda}$ spatial distribution, the ON/OFF RF modulated $\bar{\Lambda}$ production and the search for the laser stimulated formation, support a model of $\bar{\Lambda}$ formation, discussed in Subsec. 8.5, based on the interplay of two and three-body reactions, that served as a guidance for many subsequent experiments and provided a boost for the so-called second generation of trap experiments on antihydrogen.

Many results could be useful also for ordinary atomic physics, where single particle detection is usually very difficult.

10.2. Beyond ATHENA

ATHENA has been running until the end of 2004 and in the following years, despite its success, a major upgrade of the apparatus would have been necessary in order to proceed in the direction of CPT and gravity tests. Instead a different route was followed: the apparatus was dismounted and partly used as a basis for a new experiment named ALPHA that was started at the AD by some members of ATHENA.

The main goal of ALPHA is the magnetic trapping of neutral $\bar{\Lambda}$ in an octupole magnetic trap, an important milestone in the direction of spectroscopy of $\Lambda$ at rest (i.e. trapped). In the following years ALPHA studied antiparticle storage and $\bar{\Lambda}$ production in the inhomogeneous atom-trapping field and also the $\bar{\Lambda}$ formation dynamics in the multipole trap. More recently, after some systematic studies for a signature of trapped $\bar{\Lambda}$, ALPHA obtained another result, the observation of magnetically confined atoms in their apparatus, followed by the measurement of
long survival times (up to $\sim 1000$ s) of trapped antihydrogen\textsuperscript{112,113} and the observation of a resonant interaction of microwave radiation with the internal quantum states of trapped $\bar{H}$ atoms.\textsuperscript{114} In addition, in 2013 ALPHA was able to set very general limits on the gravitational force on antihydrogen;\textsuperscript{115} however, this limit needs to be defined in a more precise way.

Also the ATRAP2 collaboration pursued a similar approach, but with a quadrupole-based Penning–Ioffe trap, and succeeded in demonstrating $\bar{p}$ confinement\textsuperscript{116} and $\bar{H}$ production\textsuperscript{117} in their magnetic trapping fields.

In parallel to ATHENA and ATRAP, the experiment ASACUSA is also running at the AD since the beginning of the accelerator activities: it was initially focused on the study of antiprotonic helium, a system made of an helium atom where one of the electrons is replaced by a $\bar{p}$ that, due to the heavier mass of the antiproton, shares properties of atomic and of molecular systems and is therefore very interesting to study. The main results from ASACUSA in this field concern high precision spectroscopy of antiprotonic helium\textsuperscript{98,99} with a high precision measurement of the antiproton–proton mass ratio that is now included in the CODATA library\textsuperscript{118} and on the $\bar{p}$–He$^+$ high precision spectroscopy. In addition, ASACUSA performed new measurements of the antiproton–nucleus annihilation cross-sections at low energy on medium and heavy nuclear targets, a research field that dates back to the LEAR physics program of CERN with the PS179 experiment,\textsuperscript{119} obtaining results consistent with the theoretical expectations.\textsuperscript{120} Finally, in recent years also ASACUSA interest moved towards $\bar{H}$ and the experiment demonstrated the production of $\bar{H}$ in the fields of a magnetic cusp trap\textsuperscript{121} and has just demonstrated the feasibility of an extracted $\bar{H}$ beam, an important step towards antihydrogen in-flight spectroscopy.\textsuperscript{122}

Nowadays other experiments have completed the construction of their experimental apparatus, like AEGIS, or are just approved by CERN, like GBAR and they intend to make progress in the comprehension on the antihydrogen physics.

AEGIS\textsuperscript{123} is planning to form $\bar{H}$ at very low temperature (in the order of $\sim 100$ mK) and to extract an atomic beam from the recombination region. Since from the ATHENA results the weakly bound $\bar{H}$ population from the TBR seems to be dominant, the $\bar{H}$ formation mechanism explored by AEGIS will be the resonant charge-exchange of cold $\bar{p}$ with positronium (Ps) excited to a selected Rydberg state ($n > 20$) through the reaction:

$$\text{Ps}^* + \bar{p} \rightarrow \bar{H}^* + e^- .$$  \hspace{1cm} (17)

Ps will be produced by implanting $e^+$ at kinetic energies of several keV into a wafer of nanoporous insulator, which acts as a highly efficient Ps converter. An antihydrogen beam will be produced by controlled acceleration in an electric-field gradient (Stark acceleration). The deflection of the horizontal beam due to its free fall in the gravitational field of the earth will be measured with a moiré deflectometer. The goal of AEGIS is to perform the first direct measurement of the
gravitational interaction between matter and antimatter and, initially, the gravitational acceleration will be determined to a precision of 1%, requiring the detection of about $10^3 \bar{H}$ atoms. An improvement of the precision is expected by decreasing the $\bar{H}$ temperature. The experiment is expected to have the first results by 2016.

The GBAR experiment is also working towards a better understanding of the gravitational interaction for antimatter by studying the free fall of trapped $\bar{H}$ at rest (i.e. at extremely low temperatures, of the order of $\mu$K).

GBAR will first confine positive $\bar{H}^+$ ions in an ion trap together with ultracold laser-cooled ions (such as $\text{Be}^+$), and utilize sympathetic cooling. The ultracold $\bar{H}^+$ can then be irradiated with a laser pulse to photodetach and neutralize it. This laser pulse can also define the start timing for a measurement of the time-of-flight of $\bar{H}$ falling to an annihilation detector located some 100 mm below the trap. From this time-of-flight, the $\bar{H}$ gravitational acceleration $\bar{g}$ can be determined with a relative precision of $10^{-2}$ when 500,000 $\bar{H}$ at a temperature of 20 $\mu$K are used.

For the short/medium-term future developments in antihydrogen physics, a major upgrade of the AD at CERN is foreseen after 2016 with the construction of the ELENA ring: the new machine will slow the AD extracted $\bar{p}$ to a kinetic energy of about 100 keV: this is expected to increase the antihydrogen yield for the experiments by a factor 100.

So the antihydrogen community is very active and after ATHENA all the new developments briefly described are opening the road to the feasibility of high precision experiments on neutral antimatter at the AD. CERN remains the only laboratory in the world where antiprotons are available and where antihydrogen physics experiments can be conducted. In the long-term future many other experiments will also be possible at the proposed FLAIR (Facility for Low-energy Antiproton and Ion Research) accelerator at GSI where cooled beams of antiprotons at energies below 100 keV are foreseen. This will allow for a much higher rate of trapped antiprotons and therefore greatly advance the currently performed experiments.

References

The ATHENA experiment for the study of antihydrogen

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The ATHENA experiment for the study of antihydrogen