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Low-energy antimatter experiments at the antiproton decelerator at CERN: Testing CPT invariance and the WEP

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Low-energy antimatter experiments at the antiproton decelerator at CERN: Testing CPT invariance and the WEP

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Abstract. The riddle of the baryon asymmetry, i.e. the matter antimatter imbalance in the universe can be addressed by comparing matter particles with their antimatter counterparts. At the antiproton decelerator (AD) at CERN several antimatter experiments investigate whether CPT (charge-parity-time reversal) invariance and the WEP (weak equivalence principle) hold. The systems probed are antihydrogen ($\bar{H}$), antiprotonic helium and individual antiprotons ($\bar{p}$). This article is meant to give an overview of the experiments located at the AD, discuss some commonly used experimental techniques and point out what the different experimental approaches entail. The research done on low-energy antimatter systems can be seen as complementary to the high energy research carried out at CERN and elsewhere: It provides bounds on CPT invariance and directly addresses the question of whether the WEP holds for antimatter. It is noted that the AD - at the moment - is the only low-energy antiproton source on earth.

1. Introduction

Despite the striking success in deciphering the inner workings of matter in particle physics, there is so far no answer to a simple question stemming from cosmology - the matter-antimatter asymmetry. In the standard model of the Big Bang, matter and antimatter are supposed to be created in equal amounts. While the cosmic microwave background photon density - the remnant of the annihilation of most matter with antimatter - is a bit less than 10^9 photons per cubic metre, there is, on average, less than 1 matter particle per cubic metre in the universe giving rise to a baryon to photon ratio of $\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$(see e.g. [1], p. 7, 11). So far, we have not seen any primordial antimatter in the universe. An excess of about one baryon, i.e. a ratio of 1 000 000 001 : 1 000 000 000 (baryons : antibaryons) could therefore account for the asymmetry.

In 1967 Sakharov proposed that there could have been an imbalance in the baryon to antibaryon number in case three conditions were fulfilled: (1) CP violation in the laws of physics, (2) Baryon number violation and (3) a period of the early universe, that was out of thermodynamic equilibrium, see [2] and [3], p. 98. Sakharov's argumentation is based on an expanding universe, that requires a superdense intial state of matter and therefore seems to outrule macroscopic compartments of matter and antimatter in the universe.

A theory of a fragmented or patchwork universe with volumes of matter adjoining volumes of antimatter could still survive assuming the domains are of the size of our visible universe [4, 5]. Exploring the possibility of antigravity [6], i.e. a gravitational repulsion of matter and antimatter, it is even imaginable that the fragments/domains could have coexisted being spacially separated.

The nature of all these considerations about the mystery of the missing antimatter is speculative. Thorough experimental tests of charge-parity-time reversal (CPT) symmetry and weak equivalence principle (WEP) are, step by step, shedding light on the various speculations that have emerged since Dirac developed the notion of and postulated antimatter in the years 1928-1931 [7], p. 46.

At present the antiproton decelerator (AD) at the European Organisation for Nuclear Research (CERN) is the only place that provides low-energy antiprotons worldwide. 6 collaborations that all focus on low-energy antimatter physics are operating or are setting up their experiments.

The ALPHA, ASACUSA, ATRAP and BASE experiments (when listed, the names of the experiments occur in alphabetical order) are focussing on precision tests of CPT symmetry comparing antimatter with matter. Any deviation in a property of antimatter from the same property in matter, e.g. the resonance frequency of the 1S to 2S spectroscopy in (anti)hydrogen, would immediately indicate CPT symmetry violation.

The AE$\bar{g}$IS, ALPHAg and GBAR experiments pursue tests of the WEP by determining the sign and absolute value of the gravitational acceleration $\overline{g}$ of antimatter in Earth's gravitational field. So far no conclusive direct test of the WEP has been carried out, so it cannot be definitely excluded that an antibaryon-antilepton system like antihydrogen might fall up. However, under the assumption of exact CPT symmetry a comparison of the cyclotron-frequency measurements of (anti)protons (as well as positrons and electrons) lead to constraints on the possible deviation of the local acceleration for matter g and antimatter $\bar{g}$ [8]: For an effective gravitational potential U for matter, $\alpha_g U$ gives the effective gravitational potential for antimatter. The parameter α_g expresses the possible gravitational deviation. The most recent comparison of the antiproton-to-proton charge-to-mass ratio with the BASE experiment gave a constraint of $|\alpha_g - 1| < 8.7 \times 10^{-7}$ [9] assuming scalar gravitational interactions.

The systems investigated to probe CPT symmetry range from individual antiprotons (ATRAP, BASE), antihydrogen atoms (ALPHA, ASACUSA, ATRAP) to antiprotonic helium (ASACUSA). Since antihydrogen is uncharged and fully comprised of antimatter (lepton-baryon system) all WEP experiments aim at making use of the antiatom in their experimental schemes (AE$\bar{g}$IS, ALPHAg and GBAR).

The prerequesites to testing either CPT symmetry or WEP in the domain of low-energy antimatter physics are to efficiently trap and cool antiprotons in a Penning-Malmberg trap or to form a beam of antiprotons cold enough so it can be more easily manipulated (e.g. focused to a smaller diameter) and used in an experimental protocol.

If antihydrogen formation is required, i.e. in all collaborations at the AD except for BASE, there are two different ways to go: The older and therefore well-tested way - which is commonly refered to as 'mixing' - is to form antihydrogen via three-body collisions of antiprotons and positrons [10, 11]. The other method is a charge-exchange reaction between an antiproton and a Rydberg positronium (i.e. a blown-up electron-positron quasiatom) in which the antiproton 'steals' the positron of the positronium to form antihydrogen and sets the electron free [12].

Since the experimental methods of trapping and cooling antiprotons, positron preparation as well as antihydrogen formation are shared across many of the experiments, we will give a brief overview of the methods in Section 2.

In Section 3 we will first describe the individual experiments testing CPT symmetry. Afterwards, the experiments testing the WEP will be explained (like above the experiments will be listed according to topic, then alphabetically). Section 4 comprises a summary of the experiments presented and Section 5 gives an outlook on near-future and future low-energy antimatter physics.

For a reminder of WEP and CPT theorem please have a look at [13] and [14]. Note that this article does not discuss subexperiments at the AD that do not focus directly on CPT or WEP.

2. Trapping of antiprotons & antihydrogen formation

As addressed in the introduction a precise investigation of an entity involving spectroscopy or free fall requires to cool it down and localise it in a suitable trap/environment. Since the antiprotons mostly determine the antihydrogen formation temperature they need to be cold. After their creation they are therefore decelerated/cooled down by the AD. They are further electrostatically decelerated and/or trapped by an experiment and further cooled down within a trap.

In most experiments (ALPHA, AE$\bar{g}$IS, ASACUSA and ATRAP) positrons are obtained from a radioactive isotope of sodium. The energetic positrons coming from the Na^{22} source are moderated, buffer-gas cooled and accumulated.

Antihydrogen formation can be achieved via 'mixing' positrons with antiprotons at sufficiently high positron densities (typically achieved in Penning-Malmberg traps) or through a charge-exchange reaction between an antiproton and a positronium 'quasi'-atom.

An insight into the cooling and trapping of antiprotons, the preparation of positrons from a radioactive source (for positron production via a small linear accelerator, see Section 3.7) as well as the conditions necessary for the two different antihydrogen production methods are given in the following.

2.1. Cooling and trapping

The antiprotons are first created in the target region of the AD via 26 GeV/c protons impinging on a target leading to pair production. After their creation the antiprotons are extracted via a magnetic horn (also known as Van der Meer horn) from the target region [15, 16] and injected into the AD ring. There they are first stochastically and then electron-cooled from 3.57 GeV/c to 100 MeV/c before they are injected into the experiment beam lines after roughly 110s, see Fig. (1).

Most experiments then use a degrader foil that lowers the energy of parts of the beam to the order of 10keV/c, but also annihilates and scatters a great part of the impinging antiprotons. The limit in trapping efficiency in the commonly-used Penning-Malmberg traps is about 1% partly due to the limited trapping voltages of $5 - 9$keV and the impinging antiproton bunch kinetic energy, partly because of the losses in and due to the scattering in the degrader foil [17].

Another decelerator - the Extra Low Energy Antiproton (ELENA) ring - is currently in its comissioning phase. It will further lower the antiproton bunch energy and increase the trapping efficiency of the experiments by a factor of ~ 100 [18].

2.2. Penning-Malmberg traps

Penning-Malmberg traps, see Fig. (2), are composed of static magnetic and electric fields. They confine charged particles radially via an $E \times B$ drift and axially via electric potential wells. The majority of the AD experiments use Penning-Malmberg traps due to the long trapping times (static E and B field) and the high number of particles that can be stored. They also offer a wide range of applications spanning from various cooling techniques (e.g. electron cooling, resistive cooling) to precision single-particle frequency measurements [19].

The trap configurations used in the AD experiments are often composed of several tens of cylindrical electrodes placed in the homogeneous field of a superconducting magnet.

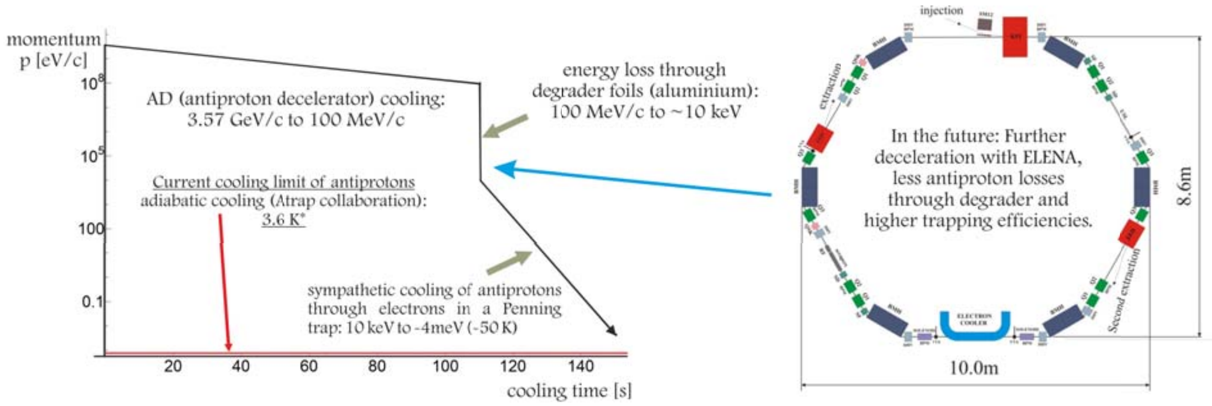

Figure 1. On the left: Kinetic energy of antiprotons in the AD ring, energy drop due to degrader foil and due to sympathetic cooling via electrons in the trap systems as a function of time. On the right: Sketch of the Extra Low ENergy Antiproton (ELENA) ring - an upgrade to the AD which will increase the cooling of the beam and thus permit much better antiproton trapping efficiencies in the experiments. *The present cooling limit of 3.6 K of an antiproton plasma is reached through adiabatic cooling [20].

Commonly shared across the great part of experiments is the trapping and cooling which is carried out as follows: Before the antiprotons are caught electrons are loaded into the trap and cool down via the emission of cyclotron radiation until they approach the equilibrium temperature (of the order of 40K) of the cryogenic environment. Antiprotons are caught in between two high-voltage electrodes and cool down via collisions with the electrons. The lowest temperature measurement of an antiproton plasma measured at the AD according to the author's knowledge is 3.6K and involved an adiabatic expansion after electron-cooling the antiproton ensemble in the trap [20].

2.3. Positron moderation, cooling and accumulation

In most experiments at the AD positrons are obtained as a pulsed beam from a radioactive source (for a different method see Sec. 3.7 about the GBAR experiment). The sodium isotope Na^{22} which is typically used emits high energy positrons in a reverse-β decay with a maximum energy of 543 keV.

In an experimental setup the Na^{22} source is located at the bottom of a parabolic or conical opening of a cryogenic copper holder. The positrons are emitted into 4π, however by means of a titanium block a fraction of the positrons otherwise lost is back-reflected [21]. The positrons are preferentially directed toward the opening of the holder where they thermalise while they pass through a solid neon moderator grown at a temperature of about $5-9$ K on the holder surface [22]. Due to the positive work function of solid neon [23] the thermalised positrons exit the moderator with a well-defined energy and form a monoenergetic positron beam.

The moderated positrons are then guided along magnetic field lines into a buffer-gas Penning-Malmberg trap often referred to as Surko-type trap [24, 25]. Initially, the positrons cool via collisions with N_2 molecules ($e^+ + N_2 \rightarrow e^+ + N_2^*$), a process that at sufficiently low pressures competes with positron annihilation through positronium formation ($e^+ + N_2 \rightarrow Ps + N^+{}_2$). The cooling of positrons by means of a specific buffer-gas is limited. At too cold temperatures positrons annihilate through the positronium channel rather than cool. A second buffer-gas such as CF_4 or SF_6 is often employed in a different trap or part of the trap to cool the antiparticles to lower temperatures than possible with N_2.

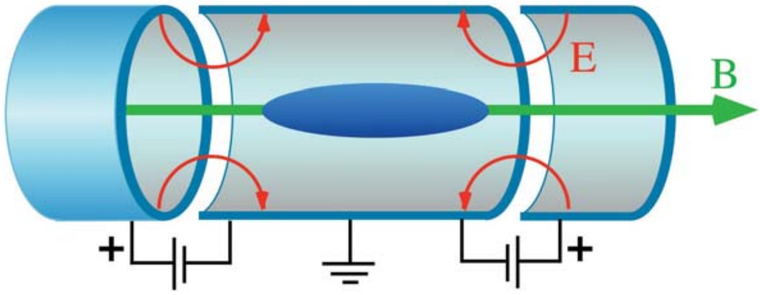

Figure 2. Charged particles are confined in a Penning-Malmberg trap via strong magnetic and electric fields. The magnetic field (in the AD experiments it is typically 1T to 5T) continually diverts the particles and forces them to orbit around the trap center as well as to undergo a cyclotron motion [19]. The electric field applied by the ring electrodes impedes the particles from exiting on axis. In short - they are trapped.
The aforementionend cyclotron motion causes the trapped particles to emit synchrotron radiation, more so for lighter particles. As a consequence electrons and positrons emit so much radiation that they approach equilibrium with the (cryogenic) environment while antiprotons do not cool by themselves. Image courtesy of [26].

The positrons are repeatedly released from the trap. Varying from one experimental setup to the next the particles are either accumulated in another Penning-Malmberg trap where they can be further buffer-gas cooled or retrapped in a stronger magnetic field with a lower background pressure where they cool through cyclotron radiation. With the techniques described above positrons can be stacked to high numbers of about 10^8 and classify as non-neutral plasmas. As has been shown in the Surko group positrons can also be stored in a multi-cell trap from which they can be released in greater numbers $\sim 10^{15}$ [27].

2.4. Antihydrogen formation via 'mixing'
'Mixing' is a three-body recombination in which two positrons and one antiproton collide at small relative velocities. One positron binds with the antiproton to form an antihydrogen atom, while the other positron carries away the binding energy.

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+ \tag{1}$$

Since it is a three-body collision the production rate of antihydrogen is proportional to n_e^2, where n_e is the positron density. The antihydrogen atom is formed in an excited state $n > 100$, where n refers to the principal quantum number.

In Fig. (3) it is illustrated how the two species 'mix' in a so-called nested Penning trap. Oppositely charged, the positrons are trapped in the center well, whereas the antiprotons are trapped in the double well surrounding the positrons, hence the name nested trap. Just like electrons, positrons are light enough to cool by means of their cyclotron radiation to the cryogenic temperatures of the environment. They are therefore anticipated to cool the antiprotons sympathetically once the plasmas overlap.

The recombination rate of an antiproton with a positron is determined by their relative velocity. The antiproton-positron mass ratio is roughly 1800, i.e. the antiproton is a factor of

~ 42 slower than the positron at the same kinetic energy. As illustrated in [16], however, a 2eV antiproton is still slow enough to combine with a 15K positron and due to the mass ratio the formed antihydrogen will keep the energy of the initial antiproton. To facilitate the formation of low-energy antihydrogen needed for spectroscopy the antiprotons can be carefully mixed with the positrons by slowly manipulating the nested trap potentials instead of simply releasing the antiproton cloud into the positron plasma like in earlier experiments [10, 11].

The formed antihydrogen is de-excited to lower quantum numbers via collisions with positrons [28]. Antihydrogen in an excited state too close to the ionisation threshold is field-ionised when it exits the field free bulk of the plasma [29].

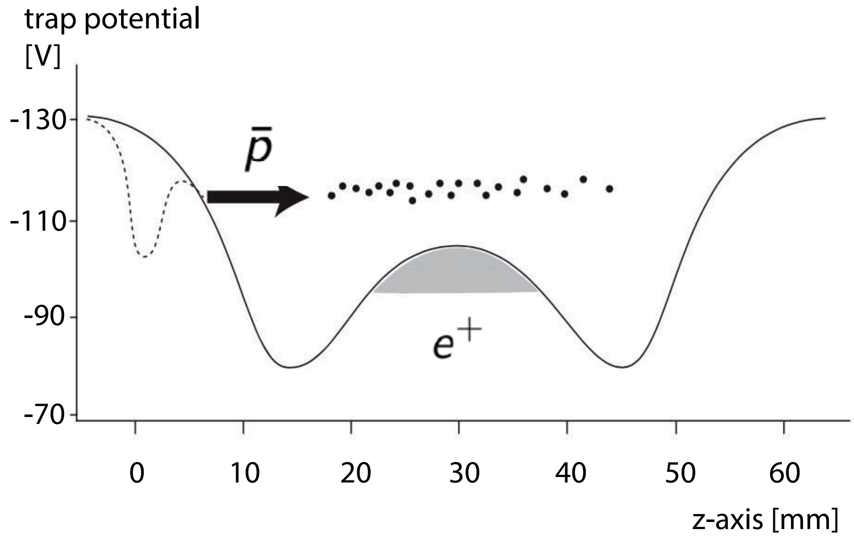

Figure 3. The antiprotons are released into an axial double well, where they cool and collide with positrons waiting in the middle of the so-called nested trap. The positrons are light enough to cool by themselves emitting cyclotron radiation into the cryogenic environment. Once the antiprotons have cooled down to energies low enough such that the relative velocities between antiprotons and positrons are small antihydrogen is formed. To form cold antihydrogen through 'mixing' it is crucial to carefully manipulate the overlap of antiproton and positron plasmas, see text. Note, that the voltage configuration depicted here is for positively charged particles. Adapted from [16].

2.5. Antihydrogen formation via charge-exchange

In the charge-exchange reaction of (Rydberg) positronium Ps^* and antiprotons $\bar{p}$

$$\bar{p} + Ps^* \to \bar{H}^* + e^- \tag{2}$$

the electron in the positronium 'quasi'-atom is replaced by an antiproton to form (Rydberg) antihydrogen. The cross section σ of the charge-exchange reaction is of the order of $a_0 n_{Ps}^4$, where a_0 is the Bohr radius and n_{Ps} the principal quantum number of positronium [30]. The highest cross section σ for a set principal quantum number n_{Ps} will be obtained for $k = \frac{v_{Ps}}{v_{orb}} < 1$, where v_{Ps} is the positronium velocity and v_{orb} the positron angular velocity [31].

Charge-exchange for antihydrogen production was demonstrated by the ATRAP collaboration in 2004 [32]. In this first demonstration Cs* atoms were used for positronium formation whereas - in the current experiments nanoporous silica targets are utilised. These targets are undergoing a lot of improvement and exist in reflection [33] and in transmission mode [34, 35]. The transmission mode positronium targets offer a much improved solid angle for positronium production as can be easily seen from Fig. (4). They however tend to be very fragile. Also the converters in transmission geometry have been proven to work with efficiency at best of about 25% of that of converters in reflection geometry.

Charge-exchange, unlike 'mixing', permits a pulsed antihydrogen production and provides antihydrogen with a more narrow quantum distribution.

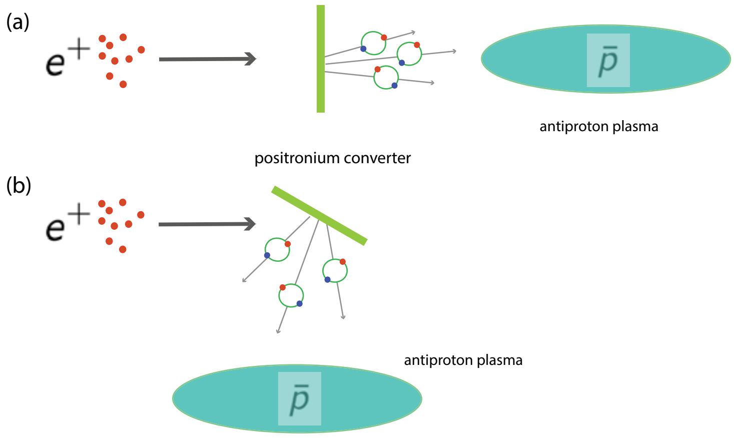

Figure 4. In scenarios (**a**) and (**b**) a bunch of positrons is released onto a transmission target and a reflection target, respectively. The solid angle for antihydrogen production is much improved in the transmission geometry compared to the reflection geometry.

3. AD Experiments

3.1. ALPHA — Antihydrogen Laser PHysics Apparatus

The ALPHA collaboration focusses on tests of CPT invariance by comparing antihydrogen transition frequencies to those precisely measured for hydrogen [36]. In 2017 they observed the 1S - 2S transition in antihydrogen trapped in a magnetic trap to a relative precision of about 2×10^{-10} [37].

The antiatoms trapped by means of their small magnetic moment in their low-field seeking states were observed in three different scenarios: (1) with the 243-nm laser light on resonance, (2) with the 243-nm laser light on, but detuned by 200kHz below the resonance and (3) with the laser switched off. Each scenario lasted about 600s and was concluded by slowly (1.5s) ramping the magnetic trap down to detect the remaining antihydrogen atoms.

The numbers detected for (2) and (3) were consistent and about twice as high as the numbers for (1) indicating that the laser on resonance had removed about 58% ±6% of the trapped antiatoms by an ionisation event or a transition to a high-field seeking state, i.e. spin-flip that would not be contained in the trap.

Other endeavours of the ALPHA collaboration include setting an experimental limit on the charge of antihydrogen [38, 39] and probing resonant quantum transitions in trapped antihydrogen atoms [40] with a similar method as described above. Recent measurements have benefitted from an increased trapping rate of antihydrogen ($\sim$ 50 antiatoms per trial). The ALPHA collaboration is also building a new experiment ALPHAg, which will focus on a test of the gravitational acceleration $\bar{g}$ antimatter experiences in Earth's gravitational field, see [41] as well as Section 3.6.

3.2. ASACUSA - Atomic Spectroscopy And Collisions Using Slow Antiprotons

The ASACUSA collaboration has two research objectives that focus on directly testing CPT invariance: (1) Spectroscopy on the ground state (GS) hyper-fine splitting (HFS) of antihydrogen and hydrogen, respectively. (2) Probing the level structure of a three-body exotic atom - antiprotonic helium [42].

ASACUSA intends to measure the GS HFS of a polarised beam of antihydrogen. This presents a different approach to the ALPHA or ATRAP collaborations, who focus on the trapping of antihydrogen, see Section 3.1 and Section 3.3.

Laser spectroscopy of antiprotonic helium allows for a precise determination of the antiproton-to-electron mass ratio. If CPT invariance holds it should be exactly the same as the proton-to-electron mass ratio.

ASACUSA also measures nuclear cross sections of antiprotons [43] at low (< 100keV) energies which will not be covered here.

3.2.1. Spectroscopy of the HFS of the GS of antihydrogen and hydrogen: Antihydrogen is formed via 'mixing' in a CUSP trap made of superconducting coils in anti-Helmholtz configuration and a stack of electrodes. While antihydrogen in its high field seeking (hfs) state is defocused in the CUSP trap and annihilates, antihydrogen in its low field seeking (lfs) state is preferentially focussed along the axis of the trap. This discrimiation leads to the formation of a polarised beam of antihydrogen.

Once outside the trap the beam passes through a Rabi module which drives the hyperfine transition(s). To discriminate the antihydrogen atoms which have made a transition from a lfs state to a hfs the beam passes through a sextupole magnet, that (like the CUSP trap) defocusses antihydrogen atoms in their hfs state. The lfs antihydrogen atoms in the beam are not deflected and counted by means of a BGO calorimeter and a 2 layer hodoscope [42].

Recently, ASACUSA measured two HFS hydrogen transitions - π_1 and σ_1 - and determined the zero-field value with the same method as described above, but for a beam of hydrogen [42]. To measure the π_1 and σ_1 transitions simultaneously the Rabi module/RF cavity was placed at 45 degrees (for the π transition the RF field needs to be oriented perpendicular to the magnetic field) and a magnetic field was oriented perpendicular to the propagation axis of the hydrogen beam [42].

As a milestone towards a comparable measurement for antihydrogen the collaboration demonstrated beam formation of antihydrogen in 2014 [44].

3.2.2. Laser spectroscopy of antiprotonic helium: Laser spectroscopy of antiprotonic helium allows for a precise determination of the antiproton-to-electron mass ratio.

The experimental procedure is as follows [45] A low-energy beam of antiprotons is being stopped in a cryogenic helium target. About 3% of the antiprotons are automatically trapped as constituents of so-called antiprotonic helium atoms. These metastable neutral systems have a lifetime of more than a microsecond and consist of a helium nucleus with an antiproton replacing the second electron.

The longevity occurs for large n (~ 38) and L (≥ 35) when the orbit of the antiproton is near-circular.

While being in a circular Rydberg state that shields the bound antiprotons from premature annihilation the exotic three-body atoms cool down to 1.5 - 1.7 K via collisions with helium atoms.

Once at cryogenic temperatures, the exotic atoms are probed. Let us assume an antiprotonic helium is in the metastable state $(n, L) = (35, 33)$. A 372.6nm laser can transfer it to the $(n, L) = (34, 32)$ state, which is short lived and Auger-decays to an ionic state $(n_i, L_i) = (30, 29)$ within les than 10ns. The ionic state in turn is very quickly destroyed by Stark collisions in the buffer gas. The annihilation signal of the now unshielded antiproton is detected [45].

In order to obtain the antiproton-to-electron mass ratio many transition frequencies have to be measured and compared to precise three-body QED calculations of the level structure of antiprotonic helium.

The cryogenic temperatures allow for a precision of the antiproton-to-electron mass ratio measurement of 1836.1526736(23) [46] which is well in agreement with the proton-to-electron mass ratio value that is known to a similar precision [47].

3.3. ATRAP — The Antihydrogen TRAP Experiment

The ATRAP collaboration dates back much longer than the other collaborations at the AD. In 2002 ATRAP was among the first two collaborations to report production of slow antiprotons via the 'mixing' technique, see Section 2.4 (the other collaboration was ATHENA which split up into the ALPHA and AE$\overline{g}$IS collaborations later on). Its predecessor was the TRAP collaboration which pioneered antiproton trapping and manipulation techniques used throughout all AD experiments.

ATRAP has measured charge-to-mass ratios of antiprotons and protons to 90 ppt [48] which was the most precise result of CERN's antiproton program before the AD. The collaboration demonstrated the feasibility of the charge-exchange reaction (see Section 2.5) to form antihydrogen [32] and successfully trap antihydrogen atoms in an Ioffe trap [49]. In 2013 ATRAP was the first experiment to measure the magnetic moment of a single antiproton [50].

The ATRAP collaboration's objective is to trap antihydrogen and perform spectroscopy on it in order to test CPT invariance. The experiment consists of building blocks very similar to those in the ALPHA apparatus. Probably the most striking difference is that the traps are stacked upon each other vertically similar to the ALPHAg but different from the ALPHA design.

As mentioned above both experiments use the 'mixing' technique to produce antihydrogen and a superimposed Ioffe trap to confine the antihydrogen atoms via their magnetic moment. The ATRAP Ioffe trap has a similar trap depth of 0.5K - confining only the few antihydrogen atoms created at very slow velocities. The main difference between the experiments is that ALPHA goes through the production and trapping cycle of antihydrogen more frequently while ATRAP makes use of higher antiproton and positron numbers for antihydrogen production[51].

3.4. BASE — The Baryon Antibaryon Symmetry Experiment

The BASE collaboration is focussing on precision measurements of the proton and antiproton magnetic moments as well as comparisons of the proton-to-antiproton charge-to-mass ratios.

They recently measured the magnetic moment of the antiproton to a parts-per-billion precision [52]. BASE also performed a high-precision comparison of the antiproton-to-proton charge-to-mass ratio with a fractional precision of 69 parts in a billion which constitutes the to date most precise test of CPT invariance in the baryon sector [53].

The experimental setup is comprised of several Penning traps at cryogenic temperatures. One of the traps serves as a catching and storage trap which confines antiprotons for more than a year [54]. The reservoir of antiprotons makes the BASE experiment fairly independent from the beam time schedules of the AD. A second trap has the purpose of efficiently cooling the particle degrees of freedom via resistive cooling.

The other two traps are precision traps used to measure the particle frequencies in two different scenarios which is refered to as the double Penning trap method, see [55]. The so-called precision trap is used to measure the proton/antiproton frequencies and the trap refered to as analysis trap is designed for proton/antiproton spin state analysis using the continuous Stern-Gerlach effect [56]. Highly-sensitive electronics and the cryogenic temperatures of the trap electrodes allow to pick up the image current signal of a single antiproton/proton in the trap. This sensitivity permits to determine the small magnetic moment of the particle by measuring the ratio of the cyclotron frequency ν_c and the spin precession frequency ν_L, which gives access to the g-factor $g = 2\nu_L/\nu_c$.

3.5. AE$\overline{g}$IS — Antimatter Experiment: Gravity, Interferometry,Spectroscopy

The AE$\overline{g}$IS collaboration aims at measuring the gravitational acceleration of antihydrogen $\overline{g}$ in Earth's gravitational field [57]. The experimental idea is to measure the deflection due to gravity of a pulsed $\overline{H}$ beam. The precise determination of $\overline{g}$ presents a test of the WEP - fundamental to special and general relativity.

Antiprotons are first captured in a Penning-Malmberg trap (4.46T magnetic field), where they are electron-cooled and compressed with the so-called rotating wall technique. Afterwards they are transfered to another trap region in a 1T field, recooled and recompressed in a trap with partially perforated electrodes.

At the same time positrons from a Na^{22} source are moderated by means of a cold head and accumulated in a Surko-type trap system that after accumulation stores, cools and compresses them [58]. The positrons are released from the trap and injected into a nanoporous positronium target which sits above the perforated electrodes. The fraction of the positronium formed in the target which lives long-enough to escape from the nano-pores is laser excited into Rydberg states, see e.g. [59]. A fraction of these long-lived Rydberg quasi-atoms passes through the perforated electrodes into the trap and forms antihydrogen through charge-exchange as explained in Section 2.5. AE$\overline{g}$IS is currently working on the antihydrogen production.

Once Rydberg antihydrogen atoms are produced they can be formed into a beam with a Stark accelerator. In a beam the Rydberg antiatoms must be deexcited into their GS before they pass through a Moiré deflectometer: two microscopic (however classical) gratings that are suitable to measure the deflection of the antihydrogen atoms over a distance of roughly 1m [60]. The antiparticles are detected by means of an emulsion [61] and/or a time-pix silica detector [62].

3.6. ALPHAg

The ALPHA collaboration is building a second experiment which is designed to test the WEP via a statistical method [63]. The experiment under construction is meant to first measure the sign of the acceleration of antihydrogen in the terrestrial gravitational field $\overline{g}$ and later make a precision measurement [64, 65].

The experimental protocol is very similar to the protocol in the ALPHA experiment, see Section 3.1. Antihydrogen is created via mixing, see Section 2.4, and the antihydrogen atoms are confined in an Ioffe trap. Unlike in the ALPHA apparatus, the trap axis of the Penning-Malmberg trap is vertically oriented.

The gravitational measurement comprises opening the Ioffe trap on axis and at both ends, which in the vertical geometry point away and toward Earth. The atoms are no longer trapped and they escape through either opening and annihilate on the Penning-Malmberg trap wall.

The gravity measurement is thus essentially converted into a counting experiment that compares the numbers of antiatoms that escaped upwards to those that escaped downwards.

3.7. GBAR — Gravitational Behaviour of Antihydrogen at Rest

The GBAR collaboration aims at testing the WEP by directly measuring the free fall acceleration of neutral antihydrogen atoms at μK temperatures [66, 67]. Their experimental scheme relies on the onset of the new ELENA decelerator which started operation in 2017, see Fig. (1). As discussed in Section 2.1 the low-energy antiprotons from ELENA permit a 100-fold (or 10-fold for ASACUSA) increased antiproton trapping efficiency, i.e. of the order of 10^7 antiprotons per bunch instead of 10^5. Via an electrostatic decelerator GBAR intends to slow the antiproton beam coming from ELENA down even further to a few keV.

To scale up in positron numbers (compared to the other experiments) GBAR is operating a small linear accelerator that produces a 10MeV electron beam that hits a Tungsten target. The energy released leads to pair production of electrons and positrons. The positrons are moderated and subsequently 'harvested' with a magnetic separator [68]. This offers a much higher flux in positrons than the flux that can be obtained with a radioactive Na^{22} source used in the other experiments that produce or aim at producing antihydrogen.

The positron beam is accumulated and further moderated in a buffer gas trap (N_2) and then transfered into a 5T Penning-Malmberg trap where the particles (just like electrons) cool down to a few meV via synchroton radiation until they reach the cryogenic temperature of their environment.

Once the energy spread is small enough the positrons are injected into a porous silica target (cf. Section 3.5) located in a reaction target where some fraction of the positrons binds with electrons to form positronium. The quasi atom gets reflected from the walls and thus exits through the nanochannels of the material. Once outside - the positronium is excited to a higher energy state (possibly $n = 2$ or $n = 3$) to improve its lifetime and enhance the probability of charge-exchange reactions with the slow (keV) antiproton beam that crosses through the chamber, see Eq. (2). A second charge-exchange reaction with already produced $\overline{H}$ atoms leads to $\overline{H}^+$ production [69]

$$\overline{H} + Ps \to \overline{H}^+ + e^- \ . \tag{3}$$

The yield of antihydrogen ions $\overline{H}^+$ will be sympathetically cooled with $^9\mathrm{Be}^+$ ions to a few μK using two Paul traps - the first one containing a few thousand of Doppler cooled Be^+ ions ($\sim$mK), the second one to perform ground state cooling of a $\mathrm{Be}^+/\overline{H}^+$ ion pair.

A photodetachment of the extraneous positron sets the antihydrogen atom free. The free fall of the antiatoms (i.e. the gravitational acceleration of antimatter $\overline{g}$) can then be measured by a set of annihilation detectors surrounding the chamber of the atom cloud. This presents a direct test of the WEP [70].

4. Discussion

From a theoretical and experimental point of view antimatter particles are the 'perfect' mirror objects. We can investigate and compare them to their matter counterparts in the search for a (minimal) difference that would indicate CPT or WEP violation. The experiments at the AD presented in Section 3 investigate relatively simple (anti)matter systems — antiprotons, antihydrogen and antiprotonic helium.

ASACUSA, see Section 3.2, aims at doing spectroscopy on antihydrogen and investigates a very exotic mixed antimatter-matter system. Antiprotonic helium lends itself to compare the antiproton-to-electron with the proton-to-electron mass ratio. ALPHA and ATRAP concentrate their efforts on antihydrogen trapping and spectroscopy while BASE focusses on the fundamental properties - magnetic moment and charge-to-mass ratio - of antiprotons and their counterparts. Complementary to these experiments designed to test CPT invariance AE$\overline{g}$IS, GBAR and ALPHAg (part of the ALPHA collaboration) all aim at measuring $\overline{g}$: (1) AE$\overline{g}$IS with (anti)matter interferometry performed on a beam of antihydrogen, (2) GBAR with ultra-cold sympathetically cooled antihydrogen ions whose temperatures are small enough that, once ionised - they can simply be dropped to measure $\overline{g}$ (3) the ALPHA collaboration aims at using a statistical method in their ALPHAg experiment which turns the gravity measurement of the sign of $\overline{g}$ into a simple counting experiment.

When looking at all the experiments in detail it becomes evident that they have a lot of experimental techniques in common. Most experiments use (or are going to use) the same trapping and cooling techniques for antiprotons and similar ones to prepare positrons. Since the antiprotons, positrons and electrons (used for electron-cooling, see Section 2.1) are often stored as non-neutral plasmas there are a number of methods borrowed from non-neutral plasma physics. One method used to compress the particles which is commonly refered to as the rotating wall (RW) technique [71] helps to store large numbers of charged particles for long times. RW also eases the preparation of the transport of plasmas from one to the other end of the long Penning-Malmberg traps used in the AD experiments.

The methods of antihydrogen production are so far two-fold: 'Mixing', see Section 2.4, is the more established technique. It has been used since the ATHENA and ATRAP collaboration synthesized cold antihydrogen atoms in 2002. Charge-exchange between an antiproton and a (Rydberg) positrium quasi atom, see Section 2.5, is less well-tried.

In 'mixing' (see Section 2.4) the positron and antiproton populations are mixed in a trap and form antihydrogen through three-body collisions. [28]. The formation rate per antiproton is proportional to the positron density squared n_e^2, which permits a high yield of antihydrogen with regard to typical densities of non-neutral plasmas inside Penning-Malmberg traps.

The antihydrogen atoms are formed at high quantum states $n > 100$. To leave the field-free plasma without being ionised by the trap potential gradient, the antiatoms have to have undergone enough collisions to relax into a lower state below the ionisation threshold [29].

The yield of antihydrogen atoms through the charge-exchange reaction (see Section 2.5) is determined by the cross section of the reaction and is proportional to the number of antiproton-positronium encounters. The cross section scales with n_{Ps}^4, where n_{Ps} is the principal quantum number of the positronium 'quasi'-atom, and critically depends on the ratio of the positron orbital velocity and the relative velocity between antiproton and positronium [30]. Charge-exchange permits a sharp onset of antihydrogen production suitable for pulsed antihydrogen beam formation, see Section 3.5. Further, the antihydrogen atoms that are formed show a more narrow and well-defined quantum state distribution than those formed through 'mixing'.

The geometry and positron to positronium conversion rate in a nanoporous silica target is very important for the charge-exchange. A lot of research is being done on how to produce stable, highly efficient transmission positronium targets. Both AE$\overline{g}$IS and GBAR collaboration use targets in reflection geometry. GBAR will work with very high particle numbers, see Section 3.7.

One of the driving forces in the advancement of low-energy antimatter physics are (as in most high precision research) newly developed methods, that often have in common that they allow higher control over the particle ensemble properties, see e.g. [72]. The precision of free fall experiments on antimatter and spectroscopy on antihydrogen as well as antiprotonic helium critically depend on the number of antiatoms available. Constantly developing as well as newly invented methods determine the experimental precision and the bounds that can be set.

Bounds on CPT invariance and WEP violation help outrule models which are part of the frameworks going beyond the standard model like the theories of the super symmetric framework (SUSY). In providing such bounds the low-energy antimatter experiments can be regarded as being complementary to the high-energy experiments at CERN.

5. Outlook

The number of available antihydrogen and antiprotonic helium atoms matters for the precision of spectroscopy experiments performed on them. In 2017 the ELENA ring started operation and will - in the future - supply the experiments with a higher number of antiprotons (a factor of about 100) at a higher rate, see Section 2.1. More antiprotons available for antihydrogen production lead to higher numbers of antihydrogen atoms that can be probed and thus higher precision in less time. The increased numbers will provide momentum to the great part of the AD experiments. In particular, the experimental schemes relying on the charge-exchange reaction (AE$\bar{g}$IS and GBAR) will benefit from the increased numbers, since the formation of antihydrogen through charge-exchange critically depends on the absolute number of antiprotons. In addition, GBAR cranks up the positron number for positronium formation via operating a linear electron accelerator instead of using a Na^{22} positron source.

In all experiments the mass of the (anti)particles involved is either measured directly or expressed in the experimental outcome. A thought suggested by Antonino Zichichi is whether we can regard (anti)hydrogen as representative of all (anti)matter since the nucleus is a single antiproton [73]. The question comes to mind whether antideuteron/deuteron would be a suitable 'mirror' pair and (anti)matter candidate instead, since the nuclei mass incorporates a nuclear binding mass term.

Seen in this light the tests of CPT and WEP could possibly have a different outcome for an antideuterion atom than for antihydrogen.

No doubt interesting could also be to perform a WEP test on protonium, also known as antiprotonic hydrogen - which is a purely baryonic system. Cold antiprotonic hydrogen production in vacuum was reported in the ATHENA collaboration in 2006 [74].

The same would be the case for the leptonic system positronium. Unlike antiprotons positrons are available without a particle decelerator. A WEP test with positronium could therefore be carried out as a table-top experiment [75].

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