Abstract

Begin by discussing the concept of antimatter and the physics principles that lead to its discovery. We then go on to describe neutral anti-atoms in the form of antihydrogen and the motivation behind studying them. We then review the experimental techniques used to capture and manipulate the constituents of antihydrogen and then go on to review the various different methods and devices used to create and trap antihydrogen. We will then review recent successes in performing measurements on the properties of antihydrogen. Finally we conclude by exploring the future developments in this field and the possible avenues that antihydrogen physics could progress down.

Introduction

A more detailed description of the the sections that will be discussed.

Description of antimatter

- **When was the concept of antimatter first introduced.**
- **What is antimatter**

The ideal of antimatter can be traced back to the end of 1890s, when Schuster discussed the possibility of the existence of antiatoms as well as antimatter solar system by hypothesis in his letter to Nature magazine A. Schuster, Nature, 1898, 58(1503): 367

The roots of antimatter physics can be traced to 1928, when British physicist Paul Dirac wrote an equation that described an electron moving close to the speed of light. He later interpreted this mathematical quirk as suggestive of the existence of an anti-electron, now called a positron, and theorized that antimatter equivalents should exist for every particle. Dirac, P. A. M. Proc. R. Soc. A 117, 610–624 (1928)

The concept of antimatter, which was introduced by Dirac between 1928 and 1931. P.A.M. Dirac, Proc. R. Soc. A 117 (1928) 610. P.A.M. Dirac, Proc. R. Soc. A 133 (1931) 60.

Antimatter was first predicted1 in 1931, by Dirac. Dirac, P. A. M. Quantised singularities in the electromagnetic field. Proc. R. Soc. Lond. A 133, 60–72 (1931).

“A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. Presumably the protons will have their own negative-energy states ...an unoccupied one appearing as an anti-proton.” P.A.M. Dirac, April 1931 letter to Van Vleck.

Antimatter particles are particles with the same mass but opposite charge as their matter counterparts.

- **What physics concepts were used to develop the initial theory**
- **Who was involved in this and what steps lead to this theory**

Special relativity: In 1905 Einstein produced his special theory of relativity [5] A. Einstein, Ann. Phys. 17 (1905) 891, 905; A. Einstein, Ann. Phys. 18 (1905) 639.. It describes the kinematics of all known classical physics in situations where gravity can be ignored. For a free particle, this theory says that the relationship between mass and(only) kinetic energy is no longer the non-relativistic.

Special relativity has part of the physics that is needed for antimatter. In particular, there is a symmetry called strong reflection [6,7]E.C.G. Stückelberg, Helv. Phys. Acta 14 (1941) 322, 588. [7] R.P. Feynman, Phys. Rev. 74 (1948) 939. This involves letting all four coordinates (space and time) be reflected through the origin. The effect of this inversion on the equations of classical electrodynamics is to change the sign of the electric charge. For each solution, then, strong reflection allows the existence of another solution. This other solution is similar to what we will call an “antiparticle” solution. However, as we observe below, it is only when quantum theory is introduced that the complete, required, antiparticle solutions appear.

The discovery of quantum mechanics: In 1912 Bohr propounded the “old quantum theory” [8] N. Bohr, Philos. Mag. 26 (1913) 1, 476, 857. His description of the hydrogen atom was a great intuitive breakthrough in quantum atomic physics. The theory quantized classical orbits, correctly predicting the energy levels of hydrogen atom.

In 1926, Schrödinger’s wave-mechanics version of quantum theory explained this result from a fundamental viewpoint [9] E. Schrödinger, Ann. Phys. 79 (1926) 361. In this new quantum theory the classical energy, momentum, and position become operators in a wave equation for the energy. In particular, the classical (non-relativistic) energy equation Eclass = p2 nonrel/2m + V (r) , (5) became i2 d dt n(r) = − 22 2m ∇2 + V (r) n(r) = Enn(r) . (6) The solution to this Coulomb potential differential equation yields the same energy levels, En, as those obtained by Bohr, but now n is the principal quantum number (one of three). Schrödinger also discovered what in modern language are called the coherent states of the harmonic oscillator [10,11] E. Schrödinger, Naturwissenschaften 14 (1926) 664 Translation of Ref. [10] in: E. Schrödinger, Collected Papers on Wave Mechanics, Blackie & Son, London, 1928, p. 41. These are the wave-function solutions of the quantum equations of motion. The wave packets follow the motion of classical particles without changing shape with time. However, wave functions are complex. Schrödinger did not understand what this meant. Schrödinger originally thought that only the “real part” of the wave function was physically significant. He wanted to ignore the imaginary part, the part which turns out to be critical to the understanding of antimatter.

Relativistic quantum mechanics:An immediate goal was to try to add special relativity to quantum ideas. Even in Bohr’s old quantum theory, Sommerfeld “added” special relativity to derive the “Sommerfeld formula” for the hydrogen-atom energy levels [13].

The next step was to try to add special relativity to Schrödinger’s operator ideas. This led to the Klein–Gordon equation [14],

This result did not agree with the hydrogen atom. We now know that the Klein–Gordon equation describes particles with internal spin-0.

The equation of Pauli incorporated the concept of spin- 1 2 electrons. Pauli gave the Hamiltonian of the hydrogen atom an added term, [1/(2m2c2r)][dV (r)/dr]L · S. Here L is the angular momentum operator. S is the spin operator, represented by a (2 × 2) matrix. Therefore, there are two solutions to the Schrödinger equation, corresponding to spin-up or spin-down.
But the Pauli equation was only a half-way house to complete understanding.

Dirac wanted to be able to avoid the analogous square root implicit in the Klein–Gordon form of quantum mechanics. He searched for some mathematical way in which the quantum operator form of Eq. (14) could be described by mc2 = [E2 − p2c2] 1/2 = [(E0 − cp ·) 2] 1/2 . (15) Then, introducing the electromagnetic potential, one could write the equation mc2 = [{E − V (r)}0 − cp ·] . (16) The four operators in Eq. (16) were (4×4) matrices. Therefore, there were four solutions to the Dirac equation, corresponding to Dirac ~ {+Espin up, +Espin down, −E spin down, −E spin up} . (17) The last two solutions have negative energies. Dirac was so scared of these solutions [21] D.F. Moyer, Am. J. Phys. 49 (1981) 944, 1055, 1120 that when he first investigated the hydrogen atom using his equation he only looked for an approximate solution 2 [18] P.A.M. Dirac, Proc. Roy. Soc. A 117 (1928) 610. It corresponded to the results of Pauli. Later, Darwin [19] and Gordon [20] W. Gordon, Zeit. Phys. 48 (1928) 11. exactly solved the Dirac equation for the hydrogen atom. They obtained the correct energy levels as Eqs. (7)–(10) with (N , L) = (n, j + 1 2) . (18) As in the Pauli equation, j is the total angular momentum quantum number, corresponding to the operator J = L + S. The negative-energy states and antimatter: Then began the fascinating fight over the meaning of the Dirac solutions. Even with Dirac's above-mentioned fear of the negative-energy solutions [21–23] W. Gordon, Zeit. Phys. 48 (1928) 11. [21] D.F. Moyer, Am. J. Phys. 49 (1981) 944, 1055, 1120. [22] H. Kragh, Arch. Hist. Exp. Sci. 24 (1981) 31. [23] L.M. Brown, L. Hoddeson, Phys. Today 35 (4) (1982) 36. 3 something obviously was right since the hydrogen atom worked so well. Dirac had to think of a physical explanation of the negative energy states. The particles described by the solutions of the Dirac equation are "fermions." Such particles have the property that only one of them at a time can occupy any energy state. In 1930 Dirac [24] P.A.M. Dirac, Proc. Roy. Soc. A 126 (1930) 360 proposed that all of the negative energy states are filled with particles, forming what is now known as the "Dirac sea." An excitation out of this sea leaves a "hole" in it. It has a positive energy and opposite electric charge to the positive-energy solution. But what were these new particles described by the holes? Dirac suggested that they were protons. This got Dirac into trouble. Bohr had rejected the physical validity of Dirac's equation.4 Bohr felt Dirac's proposal could not be the ultimate answer since there was no correspondence principle (a well defined, large-energy, classical limit) for spin, and also because negative energies were "absurd." Later, Oppenheimer pointed out that (i) the holes could not be protons because they had the wrong mass (the hole states had to have the same mass as the positive energy solutions) and further, (ii) if they had been protons they would have decayed [25] J.R. Oppenheimer, Phys. Rev. 35 (1930) 562. Faced with these criticisms, Dirac modified his holes to have the same mass as the electrons, and boldly wrote [26] P.A.M. Dirac, April 1931 letter to Van Vleck. 5 "A hole, if there were one, would be a new

kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. Presumably the protons will have their own negative-energy states ...an unoccupied one appearing as an antiproton."

- **When and where were the first discoveries of antimatter ?**

Two years later, Chao found that the absorption coefficient of hard γ-rays in heavy elements was much larger than that to be expected from the Klein–Nishima formula or any other [3, 4] C. Y. Chao, Proc. Natl. Acad. Sci. USA, 1930, 16(6): 431 C. Y. Chao, Phys. Rev., 1930, 36(10): 1519. This "abnormal" absorption is in fact due to the production of the pair of electron and its anti-partner, so-called positron. Therefore Chao's experiment is the first indirect observation of the first anti-matter particle, namely positron, in the history. Another two years later, Anderson observed positron with a cloud chamber [5] C. D. Anderson, Phys. Rev., 1933, 43(6): 491.

The discovery of the positron: The stage was now set for Carl Anderson, who in 1932 reported the discovery of the antielectron or positron, as it is now called [27,28] C.D. Anderson, Science 76 (1932) 238. C.D. Anderson, Phys. Rev. 43 (1933) 491 He was using a cloud chamber in Millikan's lab. However, this chamber had a piece of lead in it and a magnetic field perpendicular to the vertical. Therefore, high-energy cosmic rays hit the lead, made electron–positron pairs, and the two particles curved in opposite directions in the magnetic field. This showed that the two tracks came from particles with the same momentum but opposite charges. Antimatter had been discovered!

Experimentalist Carl Anderson confirmed the positron's existence in 1932, when he found a particle that seemed like an electron except that when it travelled through a magnetic field, its trajectory bent in the opposite direction. (antimatter race)

In 1930, Chao performed a few γ-ray scattering experiments on different elements [3, 4] C. Y. Chao, Proc. Natl. Acad. Sci. USA, 1930, 16(6): 431 C. Y. Chao, Phys. Rev., 1930, 36(10): 1519. γ-rays from The C after being filtered through 2.7cm of Pb were used as the primary beam. Al and Pb were chosen as the represensitives of the light and the heavy elements. For Al the γ-scattering is, within experimental error, that predicted by the Klien–Nishima formula which assumes that the removal of the energy from the primary beam is entirely due to Compton scattering of the extranuclear electrons. However, for Pb additional scattering rays were observed. The wavelength and space distribution of these rays are inconsistent with an extranuclear scatterer [3, 4] C. Y. Chao, Phys. Rev., 1930, 36(10): 1519 C. Y. Chao, Proc. Natl. Acad. Sci. USA, 1930, 16(6): 431. Later on, this abnormal absorption was identified as the outcome of the process of electron-positron pair production. Therefore this experiment was also the first experimental indiction of the first anti-matter particle, positron, in the observation history for the antimatter. Two years later, Anderson identified 15 positive tracks by photographing the cosmic rays with a vertical Wilson chamber in August, 1932 [5] C. D. Anderson, Phys. Rev., 1933, 43(6): 491 . The unknown particles were recognized as the predicted antimatter electron (positron) after an analysis of their energy loss, ionization, as well as their curvatures in the chamber. Figure 1 shows that, a positron reduces its

energy by passing through a 6 mm lead plate in the cloud chamber. The track length from the upper part of the cloud chamber can only be interpreted with the observation of positron.

The understanding of antimatter: In the following years, we came to understand more and more about antimatter. In 1935, Yukawa proposed [29] H. Yukawa, Proc. Phys.-Math. Soc. Japan 17 (1935) 48. that the strong force must be mediated by a particle of about 100 MeV rest-mass energy because it obviously was short ranged.

In 1937 Anderson and others [30–32] S.H. Neddermeyer, C.D. Anderson, Phys. Rev. 51 (1937) 884 J.C. Street, E.C. Stevenson, Phys. Rev. 51 (1937) 1005 Y. Nishina, M. Takeuchi, T. Ichimiya, Phys. Rev. 52 (1937) 1198 found a particle with a mass of about 200 times that of the electron. But it lived much too long for it to be associated with the strong force. Interestingly, however, it too came in species with both charges. This part of the story was laid to rest in 1947, when a University of Bristol group found the following processes [33] C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini, C.F. Powell, Nature 159 (1947) 694: − → − + → e− + e + + , (20) + → + + → e+ + e + + . (21) The -mesons were the Yukawa particles that mediate the strong force. The particles were the ones found by Anderson and collaborators in 1937. These muons are chargedleptons which decay weakly into the electron species of the same charge. Thus, we see that the pions, muons, and electrons come with both particle and antiparticle species. The neutrinos ( ) are the particles first postulated by Pauli to conserve energy in the beta-decay of neutrons. Eventually these particles and antiparticles were all experimentally shown to exist.

Physicists had expanded their understanding of the natural world, and took into consideration that every particle should have their antimatter partner after the discovery of positron. They were able to expand their knowledge of antimatter with the development of the technology of accelerators, while the development of Time-of-Flight detector system played an important role in the following identification of antimatter particles. In the year 1955, Chamberlain and Segr`e from University of California reported their observation of antiprotons based on the Bevatron facility [16] O. Chamberlain, E. Segr`e, C. Wiegand, and T. Ypsilantis, Phys. Rev., 1955, 100(3): 947. Antiprotons were produced and scattered into the forward direction by projecting a bunch of proton beam to the copper target at Bevatron. By observing the times of flight for antiprotons.

Discovery of the antiproton: By 1955, the Bevatron was completed at Berkeley with just enough energy (6.2 GeV) to create antiprotons. This was done by accelerating protons, colliding them with nuclei, and observing the process p + p → 3p + p . (22) The discovery is described in Refs. [34,35] O. Chamberlain, E. Segrè, C. Wiegand, T. Ypsilantis, Phys. Rev. 100 (1955) 947 E. Segrè, C.E. Wiegand, Sci. Am. 194 (6) (1956) 37. It can be tempting for physicists of our era to wonder, “Why did the discovery of the antiproton earn a Nobel Prize? Given the positron, they should have gotten the Prize if they hadn’t foundthe antiproton!” But look at the 1956 Scientific American article on the discovery of the antiproton [35] E. Segrè, C.E. Wiegand, Sci. Am. 194 (6) (1956) 37. There it says, “At this time” (1955) “several long-standing bets on the existence of the antiproton started to be paid. The largest we know of was for” (1955) “$500.

Antihydrogen

- **What is antihydrogen**
  Antihydrogen is the antimatter equivalent of hydrogen. Made of a positron and an antiproton.
  Antihydrogen, the bound state of an antiproton and a positron, has been produced. Amoretti, M. et al. Production and detection of cold antihydrogen atoms. Nature 419, 456–459 (2002) Gabrielse, G. et al. Background-free observation of cold antihydrogen with fieldionization analysis of its states. Phys. Rev. Lett. 89, 213401 (2002).

Antihydrogen is the simplest stable system of bound antimatter. The physical properties of its normal partner, hydrogen, have been studied, both experimentally and theoretically, to extremely high precision. If the same precision could be achieved with antihydrogen, a direct comparison of the two sets of results for certain specific measurements (see Section 3.2.2) could yield a most precise test of matter–antimatter symmetry. Production of antihydrogen through recombination of positrons and antiprotons has the highest rate at low relative velocity of the constituents. Precision measurements call for low Doppler shifts and long observation times. Both requirements can perhaps best be met by constructing neutral atom traps.

- **Why is it being explored**

(The antimatter race). If the experiments were to detect any difference between matter and antimatter, it would be a radical discovery. It would mean the violation of a principle called charge, parity and time reversal (CPT) symmetry. According to this principle, a mirror-image Universe that is filled with antimatter and in which time runs backwards will have the same laws of physics as our own. CPT symmetry is the backbone of theories such as relativity and quantum field theory. Breaking it would, in a way, break physics. In fact, only exotic theories predict that the antimatter experiments will find anything at all.

(Resonant quantum transitions in trapped antihydrogen atoms) The hydrogen atom is one of the most important and influential model systems in modern physics. Attempts to understand its spectrum are inextricably linked to the early history and development of quantum mechanics. The hydrogen atom's stature lies in its simplicity and in the accuracy with which its spectrum can be measured1 Ha¨nsch, T. W. Nobel lecture: Passion for precision. Rev. Mod. Phys. 78, 1297–1309 (2006) and compared to theory. Today its spectrum remains a valuable tool for determining the values of fundamental constants and for challenging the limits of modern physics, including the validity of quantum electrodynamics and—by comparison with measurements on its antimatter counterpart, antihydrogen—the validity of CPT (charge conjugation, parity and time reversal) symmetry.

(observation of the 1s2s). The Standard Model predicts that there should have been equal amounts of matter and antimatter in the primordial Universe after the Big Bang, but today's Universe is observed to consist almost entirely of ordinary matter. This motivates the study of antimatter, to see if there is a small asymmetry in the laws of physics that govern the two types of matter. In particular, the CPT (charge conjugation, parity reversal and time reversal) theorem, a cornerstone of the Standard Model, requires that hydrogen and antihydrogen have the same spectrum.

(confinement of antihydrogen for 1000 seconds) A major experimental challenge for such studies is the short intrinsic lifetimes of the exotic atoms. Atomic hydrogen is presumably stable4 , and, according to the charge–parity–time reversal theorem5 , antihydrogen—an atomic bound state of an antiproton and a positron6–8—should have the same lifetime. If sufficiently long confinement of antihydrogen can be achieved, a variety of possibilities will become available for fundamental studies with atomic antimatter. Examples include precision tests of charge–parity–time reversal through laser9 and microwave10 spectroscopy on very few or even a single trapped anti-atom; and laser11–13 and adiabatic14,15 cooling of antihydrogen to temperatures where gravitational effects become apparent *(take all references from the paper)*

(Trapped antihydrogen) Antihydrogen is of interest for use in a precision test of nature's fundamental symmetries. The charge conjugation/parity/time reversal (CPT) theorem, a crucial part of the foundation of the standard model of elementary particles and interactions, demands that hydrogen and antihydrogen have the same spectrum. Given the current experimental precision of measurements on the hydrogen atom subjecting antihydrogen to rigorous spectroscopic examination would constitute a compelling, model-independent test of CPT. Antihydrogen could also be used to study the gravitational behaviour of antimatter 5 Drobychev, G. Y. et al. Proposal for the AEGIS experiment at the CERN antiproton decelerator (antimatter experiment: gravity, interferometry, spectroscopy). Tech. Report SPSC-P-334; CERN-SPSC-2007–017 (European Organization for Nuclear Research, 2007).

(Production and detection of cold antihydrogen atoms). Antimatter, the existence of which was predicted by Dirac, can be used to test the CPT theorem—experimental investigations involving comparisons of particles with antiparticles are numerous. Hagiwara, K. et al. The review of particle physics. Phys. Rev. D 66, 010001 (2002). Cold atoms and anti-atoms, such as hydrogen and antihydrogen, could form the basis of a new precise test, as CPT invariance implies that they must have the same spectrum.

(observation of the hyperfine spectrum of antihydrogen) The goal of such studies is to search for any differences that might exist between this archetypal pair of atoms, and thereby to test the fundamental principles on which quantum field theory is constructed.

- **CPT invariance**

VIDEO

(Production and detection of cold antihydrogen atoms).A theoretical underpinning of the standard model of fundamental particles and interactions is CPT invariance, which requires

that the laws of physics be invariant under the combined discrete operations of charge conjugation, parity and time reversal.

(Production of antihydrogen) For each particle (meson, baryon, lepton, gauge boson,...) a corresponding antiparticle exists as predicted by the CPT theorem. The CPT theorem can be derived from very general principles of relativistic quantum field theory. The combined operation of charge conjugation (C), space reflection (P) and time reversal (T) represents an exact symmetry of nature. A determination of CPT invariance is therefore a test of the correctness of the description of the microscopic phenomena in terms of the existing local field theory. CPT violation would mean an existence of unknown properties of the fields and their interactions which are outside the standard theory. The search for effects of CPT violation in different processes is therefore desirable. It follows from the CPT theorem that particle and antiparticle have the same mass, spin and total lifetime and the same value but opposite sign of charge and magnetic moment. Since there is no reasonable doubt about the existence of the symmetry between particle and antiparticle, it should be possible to combine antiparticles into antimatter under the same forces as particles bind to form normal matter, in particular, to produce the simplest antiatom out of an antiproton and a positron: p.

This theorem, which was developed by Lilders [9], Pauli [101, Bell [11]
and Jost [12],

In the 1950s, the CPT theorem for quantum field theory was systematized [44–51]. In it, three quantum mechanical transformations, C= charge conjugation, P= parity, T = time reversal, are combined. In an intuitive form, the theorem says that if one were to take a motion picture of a physical process and if one then were to change the “charges” or “internal quantum numbers” of the particles in the movie (C), run the film backwards (T), and look at it in a mirror after rotating oneself by 180◦ then one would not be able to tell the difference in the laws of physics being seen. Put another way, this theorem states that every particle has an antiparticle with (i) the opposite electric charge, (ii) the opposite internal quantum numbers, (iii) the opposite magnetic moment, (iv) the same total lifetime and (v) the same (inertial) mass. CPT in quantum theory is similar to strong reflection in classical theory [44]. But in quantum theory the complex nature of the fields and equations means that CPT is equivalent to strong reflection times complex conjugation of the fundamental fields and equations.6 This new feature, the inherent complex nature of the system, is what requires the negative-energy solutions, and hence predicts the existence of antimatter. Although P, C, CP, andeven T violation have all been demonstrated, CPT has been verified in every experiment ever done. The theorem is a foundation of quantum field theory and is a description of particle physics up to and including the “standard model” of the strong, electroweak, and gravitational interactions [52]. Indeed, one does not know how to formulate a physical, mathematically consistent, relativistic, point-particle field theory that does not satisfy this theorem [2]. Even ideas of the separation of matter from antimatter in the early universe are based upon CP violation, with an accompanying T violation, that allows CPT to be conserved [53]. Even though there exist numerous experimental limits on CPT violation in the different interaction sectors [52], one should still continue to test for CPT violation in all possible sectors, since somewhere it may breakdown.

(Physics with antihydrogen) A central question of modern physics remains the apparent fate of antimatter following the birth of the Universe in the big bang. Observations are consistent with a matter-dominated Universe (though searches continue for signs of bulk cosmic antimatter; e.g., [33–36]) since the positrons and anti-quarks, presumably formed in equal quantities as their matter counterparts in the big bang, seem to have been absent when the Universe cooled enough to form atomic systems. In any case, the Universe appears not to have left us with measurable quantities of antihydrogen, and thus we are left to create it in the laboratory. It is usually assumed that the lack of observed large scale antimatter structures in the Universe implies that there are as-yet uncovered matter–antimatter asymmetries in the laws of nature [37]. One such approach to this issue is to consider whether it is possible to explain this asymmetry through details of the formation of the Universe and standard particle interactions. An example of this is the Sakharov model, proposed in 1967, where matter–antimatter asymmetry could arise through a 2 J. Phys. B: At. Mol. Opt. Phys. 48 (2015) 232001 Topical Review process in which baryon number is not conserved, violates charge–parity (CP) symmetry, and occurs out of thermal equilibrium [38]. Much effort has gone into investigating these questions, and, for instance, CP violation has been observed in a few exotic systems. References such as [39] and [40] are general reviews on this topic. However, current observations and presently accepted physics cannot explain the baryon density of the Universe [37]. Consequently, there is great interest in searching for further matter–antimatter asymmetry. One possibility is the violation of charge–parity–time (CPT) symmetry—the combined operation of charge conjugation, parity reversal and time reversal. From a theoretical viewpoint, CPT symmetry can be rigorously proven to hold in any quantum field theory that is Lorentz invariant, incorporates locality, and has a Hermitian Hamiltonian [41].

- **Antihydrogen and CPT**

(Production of Antihydrogen) Though there is hardly any doubt that no exists, it has never been observed. Once it is produced R” is certainly an ideal laboratory for studying CPT invariance by comparing interactions in matter and antimatter environments. A special challenge is the possibility of studying hydrogen and antihydrogen under essentially identical or symmetrical experimental conditions.

(physics with antihydrogen) These properties are generally taken to be axiomatic in most physical theories. A consequence of the CPT theorem is that the masses and lifetimes of antiparticles are the same as those of their matter counterparts, and that their electric charges, magnetic moments and quantum numbers have the same magnitude, but have opposite sign. Additionally, the lifetimes and eigenenergies of bound antimatter systems will be the same as the corresponding matter systems. It is this proposition that many of the AD experiments aim to probe for antihydrogen. In principle, it is possible to perform a very precise comparison with hydrogen, where the frequencies of the 1S–2S two-photon Doppler-free transition [42] and the ground state hyperfine splitting [43] are known to very high accuracies (around 4 parts in 1015 and 6 parts in 1013 respectively). For detailed discussions on which measurements may help elucidate which symmetry violations specifically see e.g. [44, 45]. Another area of physics in which matter and antimatter may

differ is gravitation. A number of groups intend to determine the acceleration of antihydrogen in the gravitational field of the Earth (see e.g., [46] for a topical update). Though there has been much theoretical speculation over the years (see e.g., [47–49] for authoritative reviews) there have been no direct experimental tests of antimatter gravity. Theoretically, general relativity predicts that the weak equivalence principle (WEP) extends to antimatter as it does for matter. Nevertheless, since gravity and quantum mechanics have resisted attempts to combine them in a consistent theory, it is clear that our understanding is incomplete. Making WEP tests on antimatter-containing systems will probe a hitherto unexplored regime and, as mentioned above, experiments are being actively developed at the AD and elsewhere (see e.g., [50–52]).

The formation of Antihydrogen

- **Overview of the most important antihydrogen experiments and the general timeline (these will be explored in more detail)**

The first antihydrogen atoms, created using antiprotons on the move, lasted about 40 billionths of a second. In 2002, two experiments, ATRAP and ALPHA's predecessor ATHENA, became the first to slow antiprotons enough to make significant amounts of antihydrogen, amassing many thousands of the atoms each5 Amoretti, M. et al. Nature 419, 456–459 (2002). The major breakthrough came almost a decade after that, when the teams learnt to trap the antiatoms for minutes at a stretch6 ALPHA Collaboration Nature Phys. 7, 558–564 (2011) . They have since measured properties such as charge and mass and used laser light to probe energy levels7Ahmadi, M. et al. Nature 541, 506–510 (2017)

Low-energy antihydrogen was first synthesized2 Amoretti, M. et al. Production and detection of cold antihydrogen atoms. Nature 419, 456–459 (2002) in 2002. This feat was later repeated7–9 Gabrielse, G. et al. Background-free observation of cold antihydrogen with field-ionization analysis of its states. Phys. Rev. Lett. 89, 213401 (2002) Andresen, G. B. et al. Production of antihydrogen at reduced magnetic field for anti-atom trapping. J. Phys. B 41, 011001 (2008). Enomoto, Y. et al. Synthesis of cold antihydrogen in a cusp trap. Phys. Rev. Lett. 105, 243401 (2010)., and in 2010 antihydrogen was successfully trapped3 Andresen, G. B. et al. Trapped antihydrogen. Nature 468, 673–676 (2010). to facilitate its study. It was subsequently shown that antiatoms could be held4 Andresen, G. B. et al. Confinement of antihydrogen for 1,000 seconds. Nat. Phys. 7, 558–564 (2011). for up to 1,000 s, and various measurements have been performed on antihydrogen in the context of tests of CPT symmetry10–12 Amole, C. et al. Resonant quantum transitions in trapped antihydrogen atoms. Nature 483, 439–443 (2012). 11. Amole, C. et al. An experimental limit on the charge of antihydrogen. Nat. Commun. 5, 3955 (2014). or gravitational studies13 Amole, C. et al. Description and first application of a new technique to measure the gravitational mass of antihydrogen. Nat. Commun. 4, 1785 (2013).

But it was not so easy. Until recently only a few atoms of antihydrogen had been produced at CERN [38] from antiproton (p) collisions with a high-Z nucleus andat Fermilab [39] in collisions between p's and hydrogen atoms. M.H. Holzscheiter et al. / Physics Reports 402

(2004) 1 – 101 9 But these were produced at relativistic speeds, much too fast to capture and study. But in late 2002, the ATHENA collaboration announced it had produced the first low-energy antihydrogen atoms (50,000 of them) [1], using antiprotons which had been trapped in a Penning trap [40] after having been extracted from the antiproton decelerator (AD) at CERN. The excitement this produced was magnified by coverage in the international press [41]. (Shortly afterwards the ATRAP experiment also announced antihydrogen production [42,43].) It is now the goal of these collaborations working at the AD to cool these antihydrogen atoms even further, confine them in possibly a magnetic trap, and to perform experiments with them. How to accomplish this is a main focus of our review.

Before performing any experiments, however, researchers required a source of antihydrogen, and for that, reliable sources of low-energy antiprotons. A flurry of activity in the field was ignited in the late 1980s by the construction of CERN's low energy antiproton ring (LEAR), a dedicated facility for high intensity, low energy antiprotons. Several techniques were proposed around that time for producing antihydrogen. These can be roughly divided into the energetic production of antihydrogen from antiprotons in storage rings and low energy production from antiprotons held in radiofrequency or Penning charged particle traps (see for example [3] for a concise perspective at the time). While the first successful demonstration of antihydrogen would be from relativistic beam experiments, production from trapped antiprotons has proved to be the fruitful way forward for making measurements on this exotic atomic system. Towards the end of the LEAR programme in 1996, the first antihydrogen atoms were produced in-flight at high kinetic energies, by the PS196 experiment [4], inspired by the proposal of Munger et al [5]. This group exploited the coasting 1.2 GeV beam in LEAR and a xenon gas target to form antihydrogen via a very rare reaction in which an antiproton interaction with the (spectator) xenon nucleus created an electron–positron (e −–e +) pair. In a fraction of cases, the antiproton and positron emerged velocity-matched and bound as an antihydrogen atom. A similar result, but in accord with available theory, was also obtained by Blanford and coworkers [6] working on the E862 experiment at Fermilab, though using a hydrogen target. Though this work confirmed expectations that antihydrogen atoms could exist, the very high kinetic energies and low production rate of the anti-atoms generated in these reactions meant that they were not suited to the type of precision studies needed to compare the properties of antihydrogen with those of hydrogen. Developments in producing cold, trapped antiprotons and positrons would lead to the next significant milestones in the study of antihydrogen. Cold antiprotons would prove critical to the production of copious antihydrogen atoms. The last thirty or so years have seen considerable progress in the types of physics experiments that can be performed with low energy, trapped antiprotons. This field was pioneered by Gabrielse and coworkers [7, 8] in the late 1980s when antiprotons ejected from LEAR were first captured and cooled in very high-vacuum, cryogenic Penning-type traps. For a decade, such experiments (see also [9–11]) were performed more-or-less parasitically to the main LEAR programme, which typically centred upon aspects of antiproton annihilation and related medium-energy physics. n order to nurture this growing field of research, CERN reconfigured its antiproton complex to ultimately commission the antiproton

decelerator (AD) in 1999 [12, 13], a novel facility dedicated to ultra-low energy antiproton physics, with antihydrogen as a prominent research topic. The first experiments at the AD were ATHENA [14], ATRAP [15] and ASACUSA [16]. ATHENA and ATRAP had the aim of producing trapped antihydrogen for eventual spectroscopic measurements, while ASACUSA had several research programs, including the spectroscopy of exotic antiprotonic systems (most notably antiprotonic helium), the production of an antihydrogen beam, and measurements of antiproton annihilation cross sections with matter. In 2005, ATHENA disbanded, with some of its members forming ALPHA [17] with new collaborators. As of 2015, the original experiments have been joined by ACE [18], an experiment dedicated to studying the effects of antiprotons on living cells, AEgIS [19], who plan to make a measurement of the gravitational acceleration of a horizontal beam of antihydrogen, and BASE [20], who are measuring the antiproton magnetic moment to high precision. A further experiment, GBAR [21], has been approved and is expected to start running after ELENA (see section 7.1) starts operation in 2017. Our review focusses on physics with antihydrogen in particular. Recent reviews that discuss other research areas at the AD (as well as antihydrogen) include [22]. In parallel with the developments in the trapping of antiprotons, great strides were also being made in capturing and cooling low energy positrons in Penning-like traps. This was based around positron beam technology (see e.g. [23] for a review in the context of antihydrogen physics) and in particular the use of the efficient buffer gas trapping technique developed by Surko and co-workers [24, 25]. This style of sourcing on-demand, cold positrons was chosen by ATHENA (see e.g. [26]) as the primary method for producing this antihydrogen ingredient. Another method for producing positrons for production of antihydrogen involved field-ionization of positronium (Ps) produced via a converter and a radioactive positron source (Na 22). Such a technique [27] was used by ATRAP in their earliest work with antihydrogen. While all currently active antihydrogen experiments employ the so-called ‘Surko-style’ accumulator to provide low energy positrons, the development of novel sources of positrons is an area of active research with at least one proposal aimed at the use of electron linac-driven pair production, followed by positron cooling and accumulation for antihydrogen experimentation [28]. With both cold antiprotons and cold positrons in place, low energy antihydrogen followed shortly thereafter. In 2002, ATHENA were the first to produce antihydrogen by the controlled mixing of trapped antiprotons and positrons [29]. This advance was quickly confirmed in a similar experiment by ATRAP [30, 31]. Many aspects of the early progress in experimentation with cold antihydrogen have been described in reviews (e.g., [23, 32]): we provide a summary of the salient achievements herein, primarily in sections 2 and 3

- **Production of positron and antiprotons**

(**Antimatter race)** By the 1950s, researchers had begun to exploit this energy-to-particle conversion to produce antiprotons. But it took decades to find a way to make enough of them to capture and study. One motivation was the tantalizing idea that antiprotons and positrons could be paired to make antihydrogen, which could then be compared with the well-studied hydrogen atom. Creating positrons is fairly straightforward. The particles are produced in certain types of radioactive decay, and can be readily caught with electric and magnetic fields. But the higher-mass antiproton is another story. Antiprotons can be made by slamming protons into a dense metal, but they emerge from such collisions moving too fast

to be held by an electromagnetic trap. Antimatter hunters needed a way to massively slow down, or cool, the particles. CERN's first dedicated attempt to decelerate and store antimatter began in 1982, with the Low Energy Antiproton Ring (LEAR). In 1995, the year before LEAR was slated to be shut down, a team used antiprotons from the facility to produce the first antihydrogen atoms 2 . LEAR's replacement, the Antiproton Decelerator, came online in 2000 with three experiments. Similar to its predecessor, it tames antiparticles, first by focusing them using magnets and then by slowing them using strong electric fields. Beams of electrons also exchange heat with the antiprotons, cooling but not touching them because the particle types are both negatively charged and so repel each other. The overall process slows the antiprotons to one-tenth of the speed of light. That is still too fast to work with, so each of the six experiments uses techniques to further slow and trap the antiprotons

(physics with antiydrogen) Antiprotons, are provided by the AD facility, located at the European Laboratory for Particle Physics, CERN [12, 13] in a manner that has been well documented. Around 1013 protons are ejected from a synchrotron with a momentum of 26 GeV/ c to strike a solid, fixed target, whereupon a few in 106 form antiprotons which can be captured by the AD via the reaction p p p p p p. 1 ++++ $^{-}$ () The initial antiproton momentum in the AD is around 3.5 GeV/c, corresponding to a kinetic energy in the vicinity of 2.7 GeV, which is much too high to be of use for antihydrogen experimentation. Using a series of deceleration and cooling sequences (see e.g., [23] for a summary) the kinetic energy in the ring is lowered to around 5.3 MeV over a period of around 100 s, with little loss of stored beam. Thereafter, a pulse of around 100 ns duration containing 3 × 107 antiprotons is ejected to an experiment.

(Antihyrogen physcis) The characteristics of the atomic recombination reaction that produces antihydrogen, and the conditions under which high-precision optical spectroscopy can be performed, effectively predetermine the positron—antiproton initial conditions to be attained for efficient recombination to occur. The essential requirement here is that the relative velocities of the constituent particles be low enough to keep them within a few atomic radii of each other during the time required to radiate a photon or interact with another suitable third body. Moreover, if the produced atom moves off at high speed, either because of initial constituent motion or recombination-induced recoil, it will not be possible to perform high-precision spectroscopic measurements on it. Thus the accumulation of significant numbers of cold antiprotons and positrons is a necessary first step in antihydrogen formation. Charged particles can be most easily cooled when they are stored in ion traps, so we must first consider the problems of trap loading with antiprotons and positrons. 2.1. Antiprotons At present the world's most copious source of low-energy antiprotons is the PS—LEAR (Proton Synchrotron—Low Energy Antiproton Ring) complex at CERN (Fig. 3) and most of the discussion which follows refers to this [82]. Protons accelerated to 26 GeV/c by the Proton Synchrotron strike a conversion target. Antiprotons of 3.5 GeV/c momentum, i.e. near the production maximum, are collected from the target and precooled in the Antiproton Collector ring and then are transferred to the Antiproton Accumulator where up to 1012 ~ can be stored for periods of weeks or even months. At regular intervals, from 15 mm to several hours, batches of i09—1010 antiprotons are skimmed offfrom the stack and decelerated in the Proton Synchrotron from 3.5 GeV/c to 600 MeV/c. This batch is then transferred to LEAR for further acceleration or deceleration and

cooling. The antiproton energy is reduced in several steps, each step being followed by beam cooling (stochastic and/or electron cooling) to reduce the adiabatic phase-space increase which inevitably accompanies deceleration processes.

(ultralow antihydrogen) Antiprotons are produced by allowing a high-intensity proton beam to impinge upon a production target. The resulting antiproton flux is capturedby a magnetic lens into a large-acceptance beam channel [88–91]. To achieve a useful number of antiprotons it is necessary that the primary beam energy be well above the production threshold of ≈ 6 GeV. This “beam–target” method is used at the two existing “antiproton factories” at Fermilab [92,93] andCERN [94,95], as well as in a number of other laboratories providing, or proposing to provide, antiproton beams (e.g., Brookhaven National Laboratory, USA; GSI, Darmstadt, Germany; JPARC, Japan). Fig. 2 (from Ref. [96]) shows the cross-section for antiproton production increasing steadily as a function of the primary proton beam momentum up to 1000 GeV/c. For a specific momentum of the primary proton beam the yield of antiprotons increases rapidly with antiproton momentum by several orders of magnitude until it reaches a maximum, typically at or below 10% of the primary beam energy. At first sight, it might appear to be advantageous to employ the highest energy proton accelerator available. Indeed, at CERN the use of the 400 GeV/c SPS instead of the 26 GeV/c PS has been repeatedly discussed. However, there are several factors which are counterproductive to the quest for high primary energy for antiproton production, especially for the case where the final goal is to reduce their kinetic energy to as low a value as possible. • Higher energy primary beams obviously require more expensive machines. • High intensity of the primary beam, which also enters into the yield, is more difficult to provide. • The optimum collection energy increases with the primary beam energy, anda higher energy collector ring is needed to profit from the increased production cross section. • At higher primary beam energies target heating quickly becomes a serious problem. • Last but not least, if the antiprotons produced are intended for low-energy applications, cooling the collected antiprotons over more and more energy decades becomes a greater challenge. From these observations we are led to the conclusion that a broad optimum for the primary proton energy exists in the region of 20–200 GeV. The higher energies are perhaps preferable for collider applications andthe lower ones are more relevant to low-energy antiproton physics, where the phase space density of the beam is the most important factor.

5.2.1. The LEAR at CERN Amongst the different antiproton facilities worldwide, only CERN has fully exploited the possibilities of antiproton physics by adding a low-energy facility to the antiproton production complex. The original complete low-energy antiproton source at CERN, shown in Fig. 4 [97], consistedof an interplay of four individual accelerators: (i) the primary proton synchrotron accelerating protons to 26 GeV/c, (ii) a large acceptance antiproton collector (AC) ring, optimizedfor 3.57 GeV/c secondary antiprotons produced in the target, (iii) a thirdring, the antiproton accumulator (AA) ring mounted concentric to the AC, in which multiple production cycles could be stacked for extended periods of time, and finally (iv) the LEAR, designed for antiproton momenta as low as 100 MeV/c.For trap experiments, which are the main topic in this review, a different mode of operation was necessary. Since the particles are captured into the trap by dynamically switching the potential on the trap structure, all particles must be delivered to the experiment in a short pulse. For this purpose fast extraction was introduced at LEAR for the first time in 1986 at a

momentum of 200 MeV/c, with a later achievement of 105 MeV/c.The fast extraction methoduseda kicker module (similar to the injection kickers) placeda quarter of a betatron wavelength upstream of the magnetic septum. This ejecteda slice from the coasting beam, containing around1–4 ×108 particles for a bunch length of 200 ns. Due to the finite p/p the remaining particles quickly spreadacross the entire ring anda second, third, etc. bunch containing fewer andfewer particles couldbe ejected. 5.2.2. The AD at CERN At the time of the LEAR shutdown, it was realizedthat a pulsed beam of antiprotons couldbe achieved by much simpler means, using an idea first introduced by Baird et al. [106]. The basic scheme consisted of utilizing the original production target set-up to produce and capture 3.57 GeV/c antiprotons in the AC. Then the AC wouldbe usednot only for the initial collection but also for added deceleration, stochastic cooling, andelectron cooling capabilities. This allows usage of just one ring insteadof the three machines (and associated beam transfer lines) requiredin the LEAR era. A preliminary feasibility study [107] was initiated through the CERN/PS Division. It was foundthat this new approach would reduce the operating cost of the facility by an order of magnitude, without significantly reducing the integrated intensity of antiprotons available for trapping experiments. Once the technical requirements of the basic scheme were understood and the feasibility was proven, the user community, ledby Holzscheiter, Yamazaki, and Faessler, initiated discussions with the CERN management [108], detailing both the machine requirements and the physics program. Initial reactions from CERN were positive so then a detailed design study for the new project, now named AD (for antiproton decelerator), was undertaken [109]. A large part of the funding required for the modification of the existing facility was generatedwithin the user community. Further, an agreement to cover a significant part of the operating cost by the users was reached. The final ingredient necessary for an unconditional green light by the CERN management, a compelling physics program, was spelled out in several letters of intent. The AD came on-line in December 1999 and delivered first antiprotons for physics experiments in April 2000. Fig. 5 shows the schematic lay-out as foreseen in 1997. (Some details on the lay-out of the experimental zones were later changed.) Antiprotons from the production target are injected at a momentum of 3.57 GeV/c, cooled and decelerated to 100 MeV/c (5.3 MeV kinetic energy), and then immediately ejected to one of the experimental areas. The machine uses the original antiproton production target from the ACOL era and, as explained above, is an adaptation of the AC ring from the LEAR era. Fig. 6 shows the deceleration cycle of the AD. In Table 2 we list the beam parameters at each momentum stage from the original design study. The antiproton momentum is lowered in two stages from 3.57 to 0.3 GeV/c, followed by stochastic cooling after each stage to reduce the momentum bite. At 0.3 GeV/c the antiproton speed is low enough for electron cooling (which is more rapid than stochastic cooling at low energies) to be applied. Electron cooling is also done following final deceleration, just prior to extraction, at 0.1 GeV/c. The entire cycle currently takes around 90 s andis capable of delivering 3 × 107 antiprotons in a pulse as short as 90 ns. An option for stacking up to ten bunches of antiprotons at 3.57 GeV/c in the AD has been described [109] but not yet implemented. This, if implemented, would potentially allow the capture of upwards of 106 antiprotons in an appropriately designed trap from a single AD shot, matching the performance of the PS200T experiment at LEAR [110]. Higher capture efficiency could be achieved by adding a stage of deceleration, such as an RFQ [82] or else an additional, ultra-low energy, storage ring like the ELENA ring proposed by Herr [111]. Discussion of the latter has recently been revived within the AD community.

(**physics with antihydrogen)** Low energy positron beams can be formed in vacuum using standard techniques (see [2, 64] for summaries), and all antihydrogen experiments to date use the isotope 22Na as a source of primary positrons, together with a solid noble gas (typically neon) moderator to produce a beam of positrons with energies of a few

(**Antihydrogen physics)** The basic mechanism behind the production of low-energy e+ is known as moderation and involves the slowing down of initially high-energy (~MeV)positrons in a solid material followed by their diffusion to a surface where they may be emitted into vacuum with a kinetic energy of the order of 1 eV. This can occur if the surface has a positron work function (~+) which is negative, something not uncommon for metals where the surface dipole barrier is favourable (i.e. it enhances instead of hindering positron evaporation [96]),or if the e+ arrive at the surface with sufficient kinetic energy to overcome a positive work function. The slow e+ thus produced can be further manipulated by accelerating or cooling if desired. The main inefficiency in e~moderation arises from the annihilation-limited e~diffusion length (102_i0~nm) in solids, which is much shorter than the mean implantation depth ofthe high energy e+. Efficiencies of fast—slow conversion therefore depend greatly upon the positron kinetic energy and vary from 10_2_10_4 for positrons from a radioactive source, to 10_6 for pair-produced fast positrons from a 100 MeV electron accelerator (see, e.g. [97,99]).The production of low-energy positrons and positronium in the cryogenic environment common in particle traps also appears feasible [100, 101], although this issue is currently controversial for the situation where clean surfaces must be prepared and maintained in ultra-high vacuum conditions [104]. One method to manipulate slow e~is to construct a beamline (see, e.g., [96,105]). A representative example, as shown in Fig. 7, is in use at University College London and delivers a continuous beam of i05 e+/s which is variable over a wide energy range [97]. The positrons are derived from a commercially available 22Na source held in close proximity to a moderator (typically a single crystal foil or tungsten mesh). Low energy e+ are confined by an axial magnetic field of around 10—2 T produced by a series of coils placed in the Helmholtz configuration. They are accelerated to 100 eY and deflected by 25 mm using an E x B filter so that the remainder of the beamline is not in the line of sight of the radioactive source. The final beam energy is fixed by the potential difference which can be placed between the isolated source—deflector region and the remainder of the beaniline. The latter is, in the instrument shown, to be mainly applied to atomic scattering studies with positrons and positronium.

(ultra low antihydrogen) This section is devoted mainly to the presentation of techniques for the creation of clouds of cold positrons which can be used to promote the formation of antihydrogen. The emphasis will be on the efforts of the ATHENA and ATRAP collaborations who have adopted different approaches to solve this problem. We will also selectively describe other demonstrated methods of positron accumulation in vacuum. First, we will briefly summarize pertinent features of the behavior of positrons and positronium at surfaces. By now this is a mature field of study, following more than three decades of research and development. Overviews have been given in previous reviews on low energy antihydrogen [127,64] andin chapter one of the monograph of Charlton and Humberston [128]. Further details can be found in the more specialist authoritative articles of Mills

[129,130], Schultz andLynn [131] andWeiss and Coleman [132]. 6.1. Positron and positronium emission at surfaces The production of low-energy positrons in vacuum following the implantation of energetic positrons (typically, and of most relevance here, from radioisotopes) into solids is central to their efficient accumulation for antihydrogen production. When positrons are implanted into materials they slow down through a variety of processes, primarily involving the creation of electron-hole pairs, phonons, andcore electronic excitations. In metallic solids thermalization of the positrons is complete on the picosecond timescale. (For comparison the typical positron annihilation lifetime in such media is two orders of magnitude greater.) In insulators (e.g., the rare gas solids) thermalization is frustrated since slowing down is prolonged when the positron energy falls below the bandgap, when electron–hole creation is no longer possible. As such, thermalization times can approach the annihilation lifetime. Once the positron has reached thermal, or near-thermal, energies it diffuses in the material. Dependent upon its initial implantation depth and diffusion length (a characteristic of the material), it may encounter the surface before annihilation. Thus, positrons implanted into materials may reach a surface in a thermal or near-thermal (termed epithermal) state. The probability of their so-doing will be in the range 0.1–1% for + particles, which typically have implantation depths extending into the m range, but of order unity for positrons injected at keV energies from a low-energy beam. Once at the surface the positron may undergo a number of processes; here we will describe the three dominant effects.8 These reactions can be summarized as: (i) emission into vacuum as a bare positron, (ii) emission into vacuum as a ground state positronium atom and(iii) capture into a surface state. It turns out, when all are allowed at a particular surface, that they have similar branching ratios.

- **Trapping techniques used on positrons and antiprotons**

(physics with antihydrogen) The basic methods to capture and cool the antiprotons were, as mentioned in section 1, developed some time ago, and utilize Penning and Penning–Malmberg charged particle trap technologies [7, 8]. These traps operate through a combination of static magnetic and electric fields. Radial (r) confinement is achieved by a magnetic field oriented along the axis of cylindrical symmetry in the trap (z) typically several tesla in strength and produced by a large solenoid. A series of voltage-biased cylindrically symmetric electrodes provide axial confinement via electric fields oriented along the z-axis that are used to form an electrostatic trap (or traps). A number of electrodes are assembled together in a cylindrical stack that allows a variety of potentials to be constructed. A schematic illustration of the full electrode assembly used in the ALPHA experiment is shown in figure 1 [53]. Penning traps are the basic workhorses of most of the antihydrogen experiments, and are used to confine and manipulate antiproton, electron and positron clouds and plasmas. A detailed review of Penning traps and the physics of confined charged clouds is beyond the scope of this review, but the interested reader may find other reviews in this area (for example, [54, 55]). For most of the antihydrogen work performed to date, antiprotons are caught dynamically by rapidly switching the voltage applied to one of the confining electrodes betweentwo static levels. In order to achieve this, the 5 MeV AD beam is moderated by thin metal foils; it is then possible to directly trap particles with energies below a few kilo-electronvolts. In the ALPHA experiment, the degrader foil, as illustrated in

figure 1, is located near the entrance of the Penning trap that faces the AD. In advance of the antiproton pulse arrival, a downstream electrode ('HVB' in figure 1, in this case) is biased to a potential of ~−5 kV while an upstream electrode (labelled 'HVA' in figure 1) is held at ground. Those antiprotons with kinetic energies below ~5 keV are confined by the magnetic field and also reflected by the potential barrier created by HVB. Before the reflected antiprotons return to the degrader, a 5 kV voltage is switched onto HVA, thus completing the capture. The capture efficiency is dependent upon the degrader material, thickness, and location as well as the magnetic field and the voltages employed by the Penning trap, and is typically a few per thousand of the AD bunch [56]. Thus, between 104 and 105 antiprotons are captured every AD cycle. Other experiments use similar procedures to capture the antiprotons. A major variation on this technique, however, is employed by the ASACUSA collaboration whereby a dedicated radio frequency quadrupole decelerator is used to lower the antiproton kinetic energy to around 100 keV, which is then followed by degradation to a few kilo-electronvolts using a thinner foil [57, 58]. The advantage of this method is the roughly tenfold enhancement in the capture efficiency of low energy antiprotons, though this comes at the expense of apparatus of significantly increased size, cost, and complexity. Before the arrival of the antiprotons in the Penning trap, an electron plasma containing around 108 particles at a density of approximately 1014 m−3 is loaded into a small trap (~50 V deep) formed by the electrodes between HVA and HVB. The trapped, energetic antiprotons pass to-and-fro along the axis of the catching trap and lose energy via Coulomb collisions with the electrons. Within a few seconds, the antiprotons have cooled to the temperature of the electrons which in turn radiate the excess energy away via cyclotron radiation. After an equilibrium is achieved, the high voltages applied to the outer electrodes can be removed as the cooled antiprotons are confined within the electrons in the shallow potential well near the catching trap centre. This capture and cooling procedure can be repeated if desired in order to generate larger antiproton populations [59]. The electron/antiproton plasma efficiently cools in the 3 T (in the case of ALPHA) magnetic field via the emission of cyclotron radiation. In principle the particles cool to the ambient temperature, which is that of the electrode stack held at 7–8 K. In ALPHA, the electron plasmas typically reach a temperature of around 100 K—presumably external sources of heating (which may include thermal radiation or voltage noise on the electrodes) prevent the plasmas from cooling further. In addition to cooling the antiprotons, the electron plasma can be used to modify the antiproton plasma density. An azimuthally segmented electrode (for example, electrode 'E04' in figure 1) can be used to apply a rotating electric field (the so-called rotating wall (RW)) to the trapped plasmas leading to compression or expansion of the combined electron–antiproton plasma (see e.g. [53, 60–62]). In ALPHA the antiprotons are always compressed to be smaller than the positron plasma (see below) to ensure good radial overlap and avoid issues with the transverse magnetic field from the antihydrogen trap (see section 4.1.1 for a description of the latter). If desired, electrons can be selectively removed by the application of pulsed electric fields while leaving antiprotons confined. By adjusting the duration (~100 ns) and amplitude of the applied pulse in a particular confining well, one can tune the number of electrons left with the antiprotons. The electrons were always completely removed before ALPHA attempted positron–antiproton mixing sequences to form antihydrogen.

ATHENA (Production and detection of cold antihydrogen) The current experiment, called ATHENA, seeks to compare the frequency of the 1S–2S electronic transition (ground state to first excited state) in hydrogen with that in antihydrogen. This frequency has been measured in hydrogen4 to an accuracy of 1.8 parts in 1014. Obtaining similar precision in antihydrogen is possible in principle, but only if very cold (of the order of a few kelvin) anti-atoms are available. Located adjacent to the antiproton decelerator5 (AD) ring at the CERN laboratory in Geneva, the ATHENA apparatus comprises four main subsystems: the antiproton catching trap, the positron accumulator, the antiproton/positron mixing trap, and the antihydrogen annihilation detector. All traps in the experiment are variations on the Penning trap6 , which uses an axial magnetic field to transversely confine the charged particles, and a series of hollow cylindrical electrodes to trap them axially (Fig. 1a). The catching and mixing traps are adjacent to each other, and coaxial with a 3 T magnetic field from a superconducting solenoid. The positron accumulator has its own magnetic system, also a solenoid, of 0.14 T. A separate cryogenic heat exchanger in the bore of the superconducting magnet cools the catching and mixing traps to about 15 K. The ATHENA apparatus7 features an open, modular design that allows great experimental flexibility, particularly in introducing large numbers of positrons into the apparatus—an essential factor in the current work. The catching trap8 slows, traps, cools and accumulates antiprotons. To cool antiprotons, the catching trap is first loaded with 3 £ 108 electrons, which cool by synchrotron radiation in the 3 T magnetic field. Typically, the AD delivers 2 £ 107 antiprotons having kinetic energy 5.3 MeV and a pulse duration of 200 ns to the experiment at 100-s intervals. The antiprotons are slowed in a thin foil and trapped using a pulsed electric field. The antiprotons lose energy and equilibrate with the cold electrons by Coulomb interaction. The electrons are ejected before mixing the antiprotons with positrons. Each AD shot results in about 3 £ 103 cold antiprotons for interaction experiments. The positron accumulator, based on a design detailed in ref. 9, slows, traps and accumulates positrons emitted from a radioactive source (1.4 £ 109 Bq 22Na). Accumulation for 300 s yields 1.5 £ 108 positrons10, 50% of which are successfully transferred to the mixing trap where they cool by synchrotron radiation. The mixing trap has the axial potential configuration of a nested Penning trap11 (Fig. 1b), which permits two plasmas of opposite charge to come into contact. In ATHENA, the spheroidal cloud of positrons can be characterized by exciting and detecting axial plasma oscillations, as demonstrated by ref. 12. Typical conditions are: 7 £ 107 stored positrons, a radius of 2–2.5 mm, a length of 32 mm, and a maximum density of 2.5 £ 108 cm23 .

(**Antihydrogen Production Using Trapped Plasmas)** At least two trapping configurations should permit two oppositely charged plasmas to overlap. A Paul radiofrequency trap confines particles via oscillatory fields and thus is able to simultaneously confine positrons and antiprotons in a single trap [18]. When such a trap is stable for positrons it is automatically stable for the heavier antiprotons as well. Simultaneous confinement ofTl~and 1 ions has observed [19]. A nested pair of Penning traps (fig. 1) is the other trap configuration. It has some possible advantages. A strong (~6 T) magnetic field is responsible for radial confinement. Appropriate potentials on a series of cylindrical electrodes (fig. 1 a), with axis in the direction of the magnetic field, produce two oppositely signed potential wells (fig. lb). A central well which can be filled with positrons is nested within a surrounding second well for antiprotons. The central well for positrons is a potential hill for antiprotons.

Antiprotons will be kept entirely out of the center region until the center hill is lowered enough to allow the antiprotons to oscillate through the positron cloud. The two-plasmas can thus be kept separate for cooling and then merged at a definite time.

ATHENA (**ultra-cold antihydrogen)** 6.2.1. Accumulation by buffer gas cooling—the ATHENA approach This method uses a Penning–Malmberg trap together with a buffer gas both to capture andalso to cool positrons from a radioactive source-based beam. The techniques used were pioneered by the University of California San Diego positron and electron groups (see, e.g., [146,147] on positrons, [148–150] on electrons, and references therein). The beam of low energy positrons is generated by using a solid neon moderator and guided into the trapping region using axial magnetic field transport. A schematic illustration of the trap is provided in Fig. 8 [152]. Positrons, with a kinetic energy of around 50 eV, enter the accumulator from the left into the 0.15 T field provided by the main solenoid magnet. The cylindrically symmetric electrode structure and a schematic of the electrical potential along the axis of the instrument are shown in Fig. 9 [153]. With the gas inlet placed at the center of the narrowest electrode a pressure gradient naturally develops along the accumulator as the electrode diameter increases. Nitrogen buffer gas is used to trap and cool the positrons. Capture occurs during the first passage of a positron through the trap electrodes if it performs an electronic excitation of the nitrogen gas. Such a transition is favored in nitrogen over positronium formation.9 About 20% of the incident positrons lose sufficient energy to be captured and are then axially confined by the electric potentials applied to the electrode array. Radial confinement is provided by the axial magnetic field. The trapped positrons continue to lose energy in collisions with the gas. They finally reside in the low-pressure region in a potential well formed by the voltages applied to the large diameter trap electrodes. One of the trapping electrodes (see Fig. 8) is split into six segments. This facilitates compression of the plasma by applying a rotating electric field, the so-called “rotating wall” technique of Huang et al. [154] and Hollmann et al. [155]. In this technique the rotating electric field transfers torque to the plasma resulting in radial compression. The method has recently been shown to work well for positron plasmas [156]. Rotating wall compression leads to heating of the plasma. Therefore, since the magnetic field in the trap is too low for efficient re-cooling using synchrotron radiation, another cooling mechanism has to be used. Greaves and Surko [156] have studied cooling by adding small quantities of various molecular gases to their rotating wall trap. Best results were found for CF4 which has the useful combination of a fast positron cooling rate and a slow annihilation rate. The ATHENA collaboration has been successful in using the nitrogen buffer gas, which is already present in the trap, to provide this cooling. This is despite the fact, as has long been known (see, e.g., [157]), that positrons lose energy slowly in this gas. The cooling was achieved because the presence of the segmented electrode in the accumulation trap ensured that rotating wall compression could be applied during the accumulation cycle. The detection system used to monitor the performance of the ATHENA positron accumulator has two main components. Both rely on the pulsed ejection of the positrons from the accumulator at the end of a trapping and holding sequence. First, there is a segmented Faraday cup detector, which can be moved in and out of the ejection beamline as illustrated schematically in Fig. 8. This detector consists of nine metal plates and can be used to extract information on the size and position of the plasma by the construction of ratios between signals detected on the various segments. The second element of the detection system is a calibrated

CsI-photodiode detector. It is used to monitor the annihilation signal generated when the positrons strike the Faraday cup. It provides a simple measure of the total number of positrons.
After the completion of the accumulation cycle, the positrons from theATHENA buffer gas accumulator must be transferred into the 3 T cryogenic region where the antiproton and mixing traps are situated(see Section 5.2.3 for a discussion of similar traps). Once the positron accumulation cycle is complete the buffer gas is pumped out. After approximately 30 s the pressure in the region at the exit of the accumulator falls below 10−9 mbar.A pulsed(duration 1 s) magnetic field of around 1 T is applied to the narrow-bore transfer section between the accumulator and the antiproton region and then the vacuum valve interconnecting the two is opened. A series of appropriate potentials is applied to the accumulator exit electrodes, the transfer electrodes, anda catching trap in the high field region such that in a time frame of a few s the positrons are squashed into a harmonic trap where they can be held for many hours if necessary. The transfer efficiency is around 50%. The accumulate-transfer-re-trap procedure can be repeated without significantly disturbing the positrons in the harmonic trap. This means the positrons can be stacked in the antihydrogen formation region [158]. Here the ensuing plasma can be further manipulated by the rotating wall technique as necessary. The positron plasma parameters of relevance for antihydrogen production can be characterized by non-destructive techniques [159,160], as described in Section 6.3.

Field Ionization of Strongly Magnetized Rydberg Positronium: A New Physical Mechanism for Positron Accumulation (ultra-low antihydrogen) The ATRAP collaboration pioneered and developed methods to directly accumulate cold positrons in a cryogenic, extreme high vacuum environment. These methods are intrinsically inefficient when compared with buffer gas cooling. However, this disadvantage is to be weighed against the more compact apparatus which is possible, enhancing ease of interface of the positron and antiproton traps. In this section we will describe only the latest scheme of Gabrielse and co-workers which involves magnetized positronium [161,162]. This work supercedes the previous efforts of van Dyck et al. [163] andHaarsma et al. [164] who accumulated positrons in similar environments by electronically damping their motion as they passed through a trapping region.

The open access Penning trap used by Estrada et al. [161], along with the electric potential and the electric field on the axis of the trap, are illustrated in Fig. 12. These fields were produced by biasing the stack of cylindrically symmetric co-axial electrodes shown in Fig. 12(a). The apparatus contains two tungsten positron moderators (a thin, transmission mode moderator and a thick reflection mode crystal) which are illuminated from the left by a 22Na + source. It is the former moderator which is of most relevance to the discussion below. A strong magnetic field of 5.3 T along the axis of the trap provides radial confinement for the + particles and the subsequently moderated positrons. The entire trap is held in a cryogenic environment at 4.2K

A non-destructive method of measuring the number of accumulated positrons was used. It is based on monitoring the Johnson noise spectrum across an RLC circuit attached to the trap electrodes [122,165]. This method was equally sensitive to electron accumulation. Fig. 13

displays accumulation rates for positrons (and electrons) in the region of the trap illustrated in Fig. 12(a). Fig. 13(a) shows that, with the appropriate electrode biasing, positrons and electrons could be accumulated at the same rate and that this rate depends upon the potential (Vt) applied to the transmission moderator. The latter quantity governs the energy with which positrons and electrons, upon leaving the moderator, traverse the distance to the trap.

The similarity of the positron and electron accumulation rates points to the mechanism involved. Estrada et al. [161] have observed that since a positron cannot, by itself, travel along the magnetic field and be trapped(if it has sufficient kinetic energy to enter the trap, it will also leave again), then the moderated positron must be accompanied by a secondary electron. Both particles are kept on near by field lines by the strong magnetic field and optimizing Vt reduces the axial spacing between them. The particles can only be accumulated in the trap if they enter as a boundpair. According to Estrada et al. [161] this occurs when their Coulomb attraction energy exceeds their kinetic energy in the center-of-mass frame and they form a magnetized Rydberg positronium atom. The electric field in the trap is then sufficient to field ionize the pair, such that either particle can be accumulated, depending upon the trap voltages. Based upon the known electric fields in the trap, Estrada et al. [161] have estimated that the positronium must have electron–positron separations in the range 1–5 m. Fig. 13(b) also shows that the yield of positrons (and by inference the yield of Rydberg positronium) is dependent upon the state of the surface of the transmission mode moderator. When the surface is cleaned by the application of laser pulses of energies up to 4 J, the Rydberg positronium yield falls to a very low value. The original yield is restored by cycling the trap and vacuum container up to 300 K followedby re-cooling to 4.2 K. Thus, the gas layer adsorbed on the moderator plays a role in enhancing the emission of Rydberg positronium, though the mechanism involved is not clear. This last observation is reminiscent of the enhanced yields of n = 2 positronium found from untreated surfaces when compared to clean metal surfaces in UHV. The difference in that case is close to an order of magnitude, with the yields from untreated surfaces being in the 1% range following bombardment of materials by positrons with kinetic energies in the order of 100 eV. A discussion of work related to the formation of n = 2 positronium in vacuum has been given by Day et al. [136]. The positron accumulation rate reported was 4 × 104(e+/h)/mCi (or around 0.3 (e+/s)/MBq) [161]. This translates into a production efficiency of the Rydberg positronium of around 2×10−6 per + particle, or around 0.2% for a moderated positron beam. This yield is surprisingly high and deserves investigation. Support for the mechanism of positron accumulation via the formation of Rydberg positronium atoms has been forthcoming from the work of Jelenkovi´c et al. [166]. The much lower accumulation rate observed by the latter may have been due to the different treatment of their moderator. This is described in the following subsection.

(Background-free observation of cold antihydrogen with Field Ionization Analysis of States) The apparatus (Fig. 1) alternates between the one used to demonstrate positron cooling of antiprotons [6] and a close copy. A 5.4 T magnetic field from a superconducting solenoid is directed along the vertical symmetry axis of a stack of gold-plated copper rings. Applied voltages form Penning traps that confine the p, e, and e and control their interactions. Captured p accumulate in the volume below the rotatable electrode. Above,

injected e accumulate simultaneously. The electrodes and surrounding vacuum enclosure are cooled to 4.2 K via a thermal contact to liquid helium. Cryopumping reduces the pressure within the trap to less than 5 1017 Torr, as measured in a similar apparatus [15] using the lifetime of trapped p as a gauge.

(**physics with antihydrogen)** The ALPHA accumulator is a three stage device where the electrodes in the successive stages progressively widen in diameter. The buffer gas is introduced into the centre of the first stage at a pressure of around 10-3 mbar and, with differential pumping on either end of the trap, the second and third stages are at pressures close to 10-4 mbar and 10-6 mbar respectively. The gas with the highest efficiency for capture so far identified is molecular nitrogen, as positron impact excitation (eNeN 2 2 + + ++ *) which involves the positron losing just under 9 eV of kinetic energy, competes favourably close to threshold with Ps formation (e N Ps N ++ 2 2 + +), which is effectively a loss channel. The three trap stages are arranged to have successively deeper electrostatic wells (by around 9 V, to match the energy loss), such that progressive collisions in the stages result in the positrons residing in the low pressure third stage. Here their lifetime can be around 100 s, such that over 108 can be accumulated in a few minutes. A RW electric field is applied using a segmented electrode in the third stage of the ALPHA accumulator [53]. This suppresses collision-induced cross-field drift of the positrons to the electrode wall such that losses are dominated by annihilation in the gas. Once the desired number of positrons has been accumulated the buffer gas supply is turned off and the gas pumped out. When the pressure has fallen below a fixed value (typically 10-8 mbar, or lower) a valve connecting the accumulator to the rest of the ALPHA vacuum system is opened and the positrons are transferred across using a well-tested procedure, whereby they are ejected in a short pulse and recaptured in the ‘positron trap’ section of the main electrode stack shown in figure 1 [63]. They then cool by emission of cyclotron radiation in the 1 T magnetic field. They accumulate in a small trap, where they can be further tailored for antihydrogen experiments using a RW. In ALPHA the positron plasma’s radial size is reduced to control the density (of importance for antihydrogen formation by the three-body process: see section 2.3) and to reduce adverse effects of the multipolar neutral atom trap (see section 4.1.1). The lifetime of the positrons in the strong-field cryogenic environment is many hours. Thus, once the transfer has been completed, the accumulator can collect further positrons, which can again be transferred, if required, to augment the number held in the ALPHA main magnet system [63].

- **Theory behind antihydrogen formation (mechanisms)**

(**Physics with antihydrogen)** 2.3. Antihydrogen formation—basic processes Antihydrogen may be formed through a number of methods, but here we restrict discussion to two broad categories that have been utilized to date. The most successful method consists of bringing positrons and antiprotons in close proximity by so-called mixing (see section 2.4). Once a mixed plasma of the antiparticles has been achieved antihydrogen is formed by an antiproton capturing a positron. The excess energy from this interaction can either be carried away by a photon in radiative recombination as e pH , 2 + + ¯ ¯ hn ( ) + or by a spectator positron in three-body recombination (TBR): e e p H e. 3 ¯ ¯ + + + ( ) ++ + The energy removed by the uncaptured positron in TBR is of the order the temperature of the plasma,

such that this process leads to weakly bound antihydrogen atoms. Experimentally, the state distribution of the nascent antihydrogen has been investigated by ATRAP [31], and the dynamics of its unintentional field-ionization studied by ALPHA [65], the results of which support this idea. It should be noted that the highly excited ('Rydberg') atoms must first decay if ground state atoms are required by the experiment. A large number of theoretical and computational studies (see e.g. [66] for an overview) have also attempted to understand both the decay process, and the mechanisms that give rise to the state distribution. There is ample experimental evidence that TBR is the dominant process for the typical parameter ranges used in mixing experiments to date. Radiative recombination may be laser-stimulated [67], as was experimentally investigated by ATHENA, but who saw no evidence of this process [68]. An alternative to formation by e^+–$\bar{p}$ mixing is the production of antihydrogen using a reaction with Ps. This scheme was one of the original proposed means of producing antihydrogen in the early days of the field (e.g. [69]). Of particular relevance is antihydrogen production via a resonant charge exchange reaction between excited Ps and antiprotons (first proposed in [70]) as $Ps + \bar{p} \rightarrow H^* + e^-$, $4 \sim a_0^2 n^*$, with a_0 the Bohr radius), which motivates the use of Rydberg states. However, such weakly bound states are susceptible to ionization by the background electric fields of the Penning trap and the motional Stark effect. These effects must be addressed and optimized for the particular experimental conditions [72, 73]. In terms of producing low-energy antihydrogen, this method has a number of immediate advantages over the mixing schemes described above, as it is not necessary to produce an excited antiproton distribution, but merely hold them at rest. Since the momentum of the antihydrogen atom is dominated by that of the antiproton, this reduces the temperature problem to one of creating cold antiprotons, a task for which techniques have already been established (see sections 4.2 and 4.3). It is not necessary to also prepare cold positrons. Also, the state of the anti-atom is relatively well defined, as the excited antihydrogen atom has a similar binding energy as the reacting Ps, which may also be advantageous. However, the requirement for producing copious Ps atoms in an excited state and having them encounter the antiprotons is a significant experimental challenge. This type of reaction mechanism is well-studied in the context of reactions with atoms and ions in Rydberg states, but reference [72] discusses a concrete scheme for producing antihydrogen. This paper proposes producing Rydberg Ps through another Rydberg charge exchange reaction with excited caesium atoms. Thus, one needs to produce a beam of excited caesium passing through trapped positrons close enough to cold antiprotons that there is a significant chance that the Ps reaches the antiproton cloud and reacts. These are significant technical hurdles in a cryogenic, extreme high vacuum environment. A proof-of-principle experiment of this nature was conducted by ATRAP, and succeeded in the production of a few antihydrogen atoms [71]. To date, use of this technique to trap antihydrogen has not been reported. Variants of the Ps resonant Rydberg charge exchange reactions are, however, proposed and under development for future antihydrogen experiments, and these are briefly discussed in section 5.

If needed look at section 3 making antihydrogen in ANTIHYDROGEN PHYSCIS

ative velocity between the plasmas. The recombination rates we shall discuss depend upon the relative velocity between antiprotons and positrons. With positrons at 4.2 K, the heavier antiprotons could have energies as high as 1 eV before the recombination rates are significantly modified. This allows the possibility of producing "beams" of antihydrogen exiting the ends of the trap by keeping the axial energy of the antiprotons substantially higher than their radial energy.

Several recombination process can be considered. In radiative recombination,

$$\mathrm{p}^- + \mathrm{e}^+ \rightarrow \bar{\mathrm{H}} + h\nu \,, \tag{1}$$

a photon carries off the extra energy which must be removed to form a bound state. The cross section and rate are small, because the time required to radiate a photon is typically longer than the duration of a collision between an antiproton and a positron. At low temperatures, the cross section σ goes inversely as the relative velocity v squared [21]. The recombination rate per antiproton, $\Gamma = n_e \sigma v$, is therefore inversely proportional to the square root of the temperature of the plasma and proportional to the positron density n_e,

$$\Gamma = 3 \times 10^{-11} \sqrt{4.2/T}\, n_e \ \mathrm{s}^{-1} \,. \tag{2}$$

Under the conditions discussed earlier ($T=4.2$ K, $n_e=10^7/\mathrm{cm}^3$ and $N_p=10^4$), the antihydrogen production rate is $N_p\Gamma=3/\mathrm{s}$.

Radiative recombination can be stimulated by an intense laser,

$$p^- + e^+ + h\nu \rightarrow \bar{H} + h\nu' \,. \tag{3}$$

perhaps to principal quantum level $n=3$ with a diode laser or to $n=10$ with a CO_2 laser. The production rate is increased from Γ to $(1+G)\Gamma$ where

$$G \approx 2\times 10^{-5} n^5 I \,\mathrm{cm}^2/\mathrm{W} \,, \tag{4}$$

at 4.2 K. This rate is limited by photoionization at high n and by achievable laser intensities at $n \leqslant 8$. Large laser intensities I could be achieved by focussing a relatively weak laser into a small recombination volume. Gains G of up to 100 could be achieved in an ion trap, comparable to gains expected with merged beams of positrons and antiprotons in a storage ring [5].

The cross section for recombination is several orders of magnitude larger if an electron or positron carries off the extra energy. One possibility is colliding positronium with antiprotons in an ion trap [6]

$$p^- + Ps \rightarrow \bar{H} + e^- \,. \tag{5}$$

However, positronium is neutral and short-lived so that it cannot be confined in the same volume as antiprotons. Moreover, the coldest available positronium beams are relatively hot (≈ 20 meV) compared to cold plasmas we are considering (<1 meV). The projected production rate [6] is thus only $N_p\Gamma=10^{-3}/\mathrm{s}$ for $N_p=10^4$ antiprotons.

We call attention to another three-body recombination

$$p^- + e^+ + e^+ \rightarrow \bar{H} + e^+ \,, \tag{6}$$

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which may well be more efficient for antihydrogen production by many orders of magnitude. Its cross section is also large because the extra positron efficiently carries off the excess energy. This process has the important additional advantage that the reactants are stable charged particles which can be held in a trap, first for cooling to meV and then until recombination occurs. Initial positron capture occurs within a few kT of the ionization limit, producing Rydberg atoms with $n>100$. The de-excitation of these highly excited states is mainly driven by collisions down to a state where there is insufficient thermal energy to collisionally de-excite. Further de-excitation proceeds via spontaneous emission.

The rate for the equivalent matter recombination, $p^+ + e^- + e^- \rightarrow H + e^-$, has been calculated in various ways [22], most recently giving [23]

$$\Gamma = 6\times 10^{-12} (4.2/T)^{9/2} n_e^2 \ \mathrm{s}^{-1} \,. \tag{7}$$

To understand the dependence on temperature and density, we note that the relevant length scale in this reaction is the Thomson radius ($R=2e^2/3kT$), at which distance the Coulomb interaction between two elementary charges is equal to the thermal energy $\frac{3}{2}kT$. Therefore

$$\Gamma \sim \frac{(n_e R^2 v\tau)^2}{\tau} \sim n_e^2 T^{-9/2} \,, \tag{8}$$

were v is an average positron velocity (which scales as $T^{1/2}$) and $\tau \approx R/v$ is the duration of the collision. The numerator is the probability for having an in-

- **Basic experimental techniques used to produce antihydrogen**

PRODUCTION OF ANTIHYDROGEN

(**Ultra-low energy antihydrogen)** 7.2. The production of antihydrogen in flight The original two experiments, those of Baur et al. [38] andBlanfordet al. [39], took place at CERN and Fermilab, respectively. Both were basedupon the original suggestion of Munger et al. [180]. A Feynman diagram depicting the process is given in Fig. 18. The basic interaction involves an antiproton andan atomic nucleus of charge Z. The cross section for this process has been the subject of several investigations. Baur [181] considered antihydrogen formation proceeding via the mechanisms of photon–photon collisions and pair production by virtual bremsstrahlung. He foundthe former, p + Z → p + 2 + Z → p + e+ + e− + Z → H + e− + Z , (43) to dominate and gave the asymptotic cross section for capture into the 1S antihydrogen state (when the antiproton Lorentz factor = Ep/mp?1) to be
1S = (33/20)Z25r2 e ln ≈ 2.7Z2 ln (pb) , (44) where is the fine structure constant and re is the classical radius of the electron. A similar result was also obtainedby Munger et al. [180] using the so-calledequivalent photon approximation. The accuracy of this approximation at the relatively low energies at which the antihydrogen experiments were performed(e.g., ≈ 1 for the work at CERN [38]) was testedby Bertulani andBaur [182]. These authors performedcalculations using a plane wave Born approximation (which is equivalent to the straight line semiclassical trajectory approximation). They foundthat the cross sections in the energy region of experimental interest were much lower than those predicted by extrapolating the equivalent photon approximation results. Indeed, they judged the latter approximation to be only of qualitative guidance below ≈ 10. T

A schematic illustration of the CERN experiment is shown in Fig. 19. Antihydrogen was formed in LEAR by interactions of antiprotons circulating at 1.2 GeV with a xenon gas target (to exploit the Z2 factor in Eq. (44)). Once formed the antihydrogen continued along the path of the antiproton, with the incoming momentum, until the first bending magnet. Here it was separated from the antiprotons and traveled along the short straight section depicted schematically in Fig. 19. Forty nanoseconds after its creation it struck the array of three thin silicon detectors. The positron was strippedoff the antiproton and, with a kinetic energy of around0.66 MeV, was stoppedin the detectors whereupon it annihilated with the emission of a pair of back-to-back 0.511 MeV -rays. These were registered in coincidence by the segmented NaI(Tl) detector which surrounded the silicon counters. The antiproton continued on its path, traversing thin scintillators to give timing information and drift chambers located before and after a bending magnet to measure its position and momentum. Signals from all of the detectors were used to isolate the antihydrogen from other particles (e.g. antineutrons) that could give fake triggers in one or more of the individual detectors. After analysis of about 15 hours of beam time distributed over a period of several days, Baur et al. [38] announced the creation of 11 antihydrogen atoms with an estimated background of 2±1 events. Baur et al. [38] estimated the integrated luminosity from the number of stored antiprotons and the thickness of the gas target. It was 5 × 1033 cm−2 ± 50% for their total running period. The acceptance of their detection system was found from test measurements and a Monte Carlo simulation to be 0.3. Taken together with the number of antihydrogen atoms produced, Blanford et al. [39] pointed out that the implied formation cross section from the CERN experiment is at least 6 nb. A schematic illustration of the FNAL experimental apparatus of

Blanfordet al. [39] is shown in Fig. 20. The experiment was run parasitically alongside an existing charmonium study at Fermilab. Hence, the target was formedby a hydrogen gas jet andthe target density andantiproton beam energy were dictated by the “host”. The results of Blanfordet al. [39] were based upon data taken between November 1996 and September 1997 with beam momenta between 5.20 and6.23 GeV/c (equivalent kinetic energies of between approximately 4.3 and5.4 GeV). Antihydrogen atoms formed with the beam momentum were separated at the storage ring dipole as shown in Fig. 20. The antihydrogen then left the storage ring and was ionized down stream in a thin carbon foil which was mounted on a device that enabled it to be remotely removed from the antihydrogen flight path. The positron and antiproton fragments (each of which roughly retained the velocity of the antiatom) were then analyzed in separate spectrometers. The positron was deflected through 40◦ andstoppedin the scintillator CE (see Fig. 20) andthe annihilation -rays monitored using a pair of half-cylindrical NaI(Tl) counters. As described in [39] the antiproton momentum was measured by a series of proportional wire chambers (PWC) andthe scintillation counters C1 andC2. Three-way coincidences were used to identify a background-free sample of 57 antihydrogen atoms. The coincidences were among the scintillators (independent of whether extra constraints were imposed by requiring a coincidence with the NaI(Tl) counter) and either PWC#2 or PWC#3 registering a hit on at least one wire. Comparisons of runs with and without the ionization foil in the beamline were also used. Further details of the analysis have been given by Blanford et al. [39], who also discuss how they derived the antihydrogen production cross section from their data. Their antihydrogen production cross section result for beam momenta between 5.20 and 6.23 GeV/c is (1.12 ± 0.14 ± 0.09) pb (statistical and systematic uncertainties, respectively). This includes factors for luminosity and acceptance corrections. This cross section is in accord with the result of Bertulani and Baur [182] who find0.91 pb at 5.7 GeV/c. However, it is the comparison of these results [182] with the original CERN experiment which gives some cause for concern. The predicted cross section for Z = 54 and an antiproton momentum of 1.94 GeV/c is around 0.67 nb, nearly one order of magnitude lower than the experimental result. Despite the large luminosity uncertainty and the poor statistics of the CERN study, theory and experiment appear to be inconsistent. Now, however, we return to the main topic of this review; namely the production of cold antihydrogen.

(Physics with antihydrogen) In mixing schemes, once antiprotons and positrons are held in neighbouring potential wells, the plasmas must be merged to form antihydrogen. Further details on how the plasmas are tailored to promote the formation of some antihydrogen with low enough kinetic energies to be trapped in a 0.5 K deep magnetic minimum neutral atom trap can be found in section 4. These manipulations are typically specific to each experiment, and may vary on a trial-by-trial basis. However, there are two generic forms of mixing, which we refer to as basic and driven, and we will briefly describe their features. We describe basic mixing first, illustrated by figure 2, which is a schematic of the on-axis electrical potential of a prototypical nested Penning trap arrangement [74] used in most antihydrogen work to date. For the purposes of this review, we discuss the operation in detail with respect to experiments on the ATHENA apparatus, though ALPHA, ATRAP and ASACUSA have used similar techniques for the production of antihydrogen [30, 75]. The figure indicates how antiprotons were released into the positron cloud from a side well with up to 30 eV of kinetic energy in the ATHENA, ATRAP and early ALPHA experiments. It was

found that the antiprotons slowed rapidly on interaction with the much more numerous positrons, and after a few hundreds of milliseconds antihydrogen (as detected by its annihilation on the trap electrodes) began to form [76]. In this manner cold antihydrogen was first produced [29] at peak rates in excess of several hundred per second [77]. A detailed analysis of the axial (i.e., along the z-direction) distribution of the antihydrogen annihilations [78] revealed that it could not be accounted for if it was assumed that the antiprotons formed antihydrogen after reaching thermal equilibrium with the assumed temperature of the positron plasma (which was taken as the ambient temperature of the ATHENA trap of 15 K). Indeed the antihydrogen temperature(s) used to fit the distributions were around two orders of magnitude higher than that value. The highly pertinent conclusion from that work was that this simple method of antiproton–positron mixing was unlikely to form antihydrogen with kinetic energies low enough to be held in a sub-kelvin-deep neutral atom trap and that other techniques needed to be developed if the goal of trapping was to be achieved. As an alternative to producing antihydrogen by launching energetic antiprotons into positrons and waiting for the excess energy to be lost by collisions, one can start with cold antiprotons 'below' the positron space charge, and drive them into the positrons in order to reduce the excess energy involved in the process. Charged particles held in Penningtype traps possess an axial bounce frequency, fz, that is the rate at which the particles traverse and return to their original position in the longitudinal (z) direction in the trap. Applying an oscillating, axially oriented, electric field at this frequency can excite the longitudinal motion of, for example, antiprotons, and give them energy to overcome the potential separating them from the positrons. In all but ideal Penning traps, the electric potential confining antiprotons is anharmonic: the frequency of the longitudinal motion will depend on the longitudinal energy of the particle, with lower amplitudes tending towards simple harmonic motion. As a consequence, driving the particles at a single frequency does not resonantly excite any individual antiproton into the neighbouring positrons. In order to initiate mixing in this manner, one relies on large driving amplitudes, and/or heating of the particle distribution to achieve injection. This technique was first demonstrated by ATRAP [31]. In that scenario, a 825 kHz drive with a 1 V peak-to-peak amplitude was applied for many seconds, with the frequency chosen to be resonant with the axial bounce frequency for antiprotons oscillating near the axis and near the bottom of their nested potential well. Further discussion of this technique is given in the review by Gabrielse [32], including details of antihydrogen detection and an exploration of using weaker radio frequency drives. The ALPHA collaboration has solved the problems associated with the distribution-heating resulting from a fixed drive by developing a chirped frequency excitation technique, based upon the phenomenon known as autoresonance, that rapidly excites all antiprotons coherently to the positron energy using low-amplitude excitation (50 mV) [79]. This mixing scheme has been used for all ALPHA trapping experiments to date, and is discussed in detail in section 4.4. In a recent demonstration of antihydrogen trapping [80], ATRAP have used another variant on the driven technique. In order to maintain resonance with the antiprotons as the axial oscillation becomes anharmonic they have applied a driving force with a frequency spectrum broadened by noise for a period of up to 10 min. Other experiments were undertaken, in a manner similar to ALPHA's autoresonant technique, using a chirped drive with the chirp duration varied for periods of between 2 ms and 15 min. No further details were provided.

8. Combining all the parts to make antihydrogen: a summary All processes to form antihydrogen depend strongly on the density of the positron plasma seen by the antiprotons. Further, many more positrons than antiprotons are needed to convert all antiprotons into antihydrogen in a reasonable time period. To accomplish this formation, ATHENA uses high-density positron plasmas andclouds of coldantiprotons in the apparatus developed [242] andcurrently configured [243] as illustratedschematically in Fig. 30. A continuous flow cryostat is usedto cool the central vacuum region to 10–15 K. Both theATHENA andtheATRAP collaborations capture antiprotons from theAD beam in an elongated Penning trap, using the foil degrading method developed at LEAR for the PS200 [123] andTRAP [124] experiments, respectively, as describedin Section 5.2.3. The capturedantiprotons are cooledto thermal M.H. Holzscheiter et al. / Physics Reports 402 (2004) 1 – 101 59 equilibrium with the ambient temperature of the surrounding apparatus by electron cooling.ATHENA runs at the AD have shown capture efficiencies of the order of parts in 103–104, in agreement with theoretical expectations for this process [1]. Currently about 10,000 antiprotons are capturedfrom a single AD pulse containing 2 × 107 particles. In both ATHENA and ATRAP positrons for the production of antihydrogen are obtained from radioactive decay of a -emitting source (22Na). The fast positrons emittedby the source are implantedinto a thin moderator, consisting either of a tungsten foil or a layer of inert gas frozen onto a substrate. There they quickly lose energy through collisions with the bulk. A fraction of the positrons can diffuse back to the surface of the moderator andbe emittedinto the vacuum either as positrons or boundto electrons as positronium atoms. Positrons for the ATHENA experiment are collectedby a system basedupon the positron accumulator developed by the group of Surko at the University of California in San Diego [146,147]. Here, as described in Section 6.2.1, one further slows down the moderated positrons from the radioactive source using inelastic collisions in a buffer gas. This methodallows one to collect 2 × 108 positrons in approximately 3 min from a 50 mCi 22Na source in a Penning–Malmberg trap [151,152]. As summarizedin Section 6.2.1, the positrons are then quickly transferredto the main ATHENA apparatus where they are captured in an harmonic trap andquickly cool (in the 3 T magnetic field) to the ambient temperature. The final positron harmonic trap, the antiproton catching trap, andthe recombination trap, are all three housedin a single, large diameter, cryogenic bore cryostat. This facilitates transfer of the chargedclouds between the individual trap sections and also helps to achieve the extreme high vacuum required for long storage times andlow backgroundannihilation. ATRAP has developed a novel accumulation scheme which yields low-energy positrons directly inside the cryogenic vacuum section of the apparatus (see Section 6.2.2). A significant fraction of the slow positrons emitted from the surface of the tungsten degrader is accompanied by slow electrons. Due to the strong magnetic fieldthese two particles can form a quasi-boundstate and, if the Coulomb interaction between the particles exceeds their kinetic energy in the center-of-mass frame, a highly magnetized Rydberg state of positronium results. This state is then ionizedby the electric fieldpresent in the Penning trap. Then, if the kinetic energy is below the well depth, either the electron or the positron can be trapped, depending on the sign of the potentials applied to the trap electrodes. The accumulation rate achievedin this manner is still significantly lower than for the case of buffer gas cooling of ATHENA, but it is orders of magnitude higher than that obtained by electronically damping the energy of low-energy positrons passing through the trap. In Ref. [161] the ATRAP collaboration reports a positron accumulation rate of 105e+h−1. Now cold, the antiprotons

are allowed to interact with the dense plasma of positrons to hopefully form antihydrogen via spontaneous radiative recombination (SRR), possibly later enhanced by laser radiation, or via three-body recombination (TBR), a process which theoretically dominates at lower temperatures and higher positron densities. Both radiative recombination and stimulated radiative recombination lead directly to low lying atomic states of the produced antiatoms. TBR predominantly yields highly excited Rydberg states which may ionize in the electric fields present in the charged particle traps if they are not promptly de-excited. As discussed in Section 7.4, the presence of a strong magnetic field can have a complicated effect on the dynamics of the recombination process. One of the biggest challenges consists in bringing the antiprotons and positrons into close contact for a time sufficiently long to allow recombination to take place. Since the low energy of the antiprotons, and hence of the antihydrogen atoms produced, is a mandatory requirement for trapping the antihydrogen atoms in a magnetic trap, it is necessary to start with the coldest possible constituents and choose a recombination method that adds little or no recoil energy to the formed antihydrogen. As described in Section 7, different methods have been proposed to combine the positrons and antiprotons, i.e. using a combined Penning/Paul trap configuration [202], injecting a (pulsed or continuous) beam of low-energy positronium atoms into stored antiprotons [213], or storing positrons and antiprotons simultaneously in nested Penning traps [203]. Of these, at least in the most basic realization of each scheme, it appears that only the last one fulfills the above requirements, andit is the method that has been used by both antihydrogen experiments. While the long-term goal of the experiments is to confine the produced antihydrogen atoms in a neutral particle trap and perform precision spectroscopy, at this early stage no neutral trap is implemented in either the ATHENA or ATRAP apparatus. To begin with, many questions concerning the production mechanism(s), the final state distribution and the temperature of the antihydrogen atoms produced need to be understood. For such studies an unambiguous identification of the produced antihydrogen is needed. The annihilation of antihydrogen atoms provides one possibility. The existence of an antihydrogen atom is signaled by the almost simultaneous annihilation of an electron–positron pair into two back-to back 511 keV gamma rays and the annihilation of an antiproton on a nucleon, producing predominantly charged pions (~ 3 plus fewer neutrals), each with an average energy of about 300 MeV. If the signals of these events are detected in a short time window, originating from the same location in space, statistical considerations rule out random coincidences by a high rejection factor, as we will discuss later. The ATHENA collaboration has constructed a detector capable of this. In contrast, the method used by ATRAP to identify the production of antihydrogen detects only antiprotons that are recaptured in a separate field region after the (excited state) atoms are ionized. Both will be described in Section 9.

Detecting Antihydrogen

- **Experimental technique behind the detection of antihydrogen**

(ultra-low energy antihydrogen) Long before one can hope to perform precision spectroscopy on trapped antihydrogen atoms it is paramount to clearly identify the production of the neutral atom from its constituents and to study the dependence of the production rate on a variety of parameters to optimize yields for future experiments. These

studies should allow first insights to final state and temperature distributions of the produced antihydrogen and may shed light on the reactions of antihydrogen atoms with normal matter at low energies. Expecting only modest production rates, detection must be performed efficiently and unambiguously in order to discriminate against different forms of background signals. The two experiments attempting precision studies of antihydrogen chose two very different approaches to this problem and ultimately both methods were demonstrated to be viable options, giving different sets of information. The ATHENA collaboration basedits detection scheme entirely on the annihilation event, obtaining spatial and temporal resolution of the production of antihydrogen, independent of the atomic state in which the antihydrogen atoms were formed. On the other hand, ATRAP determines the production of an antihydrogen atom in excited states above a certain n-state (or, more properly, below a certain binding energy) by re-ionizing the atom in an electric field and retrapping the remaining antiproton in a separate region of the trap. Using these different methods, production of antihydrogen was reported first by ATHENA [1] and very soon afterwards by ATRAP [42,43], during the latter part of 2002.

9.1.1. Charged particle detection Antiproton-matter annihilation at rest produces on average 3 charged pions with momenta around 265 MeV/c. These particles must first traverse the trap electrodes, the walls of the inner dewar, the wall of the surrounding vacuum vessel, and finally the walls of the enclosure of the detectors. Multiple scattering in these layers leads to an uncertainty of the annihilation vertex position of about 0.5 mm. The accuracy of the hit measurement in each of the two layers of the silicon strip detector was matched to this extrapolation accuracy. The microstrip modules consist of two double sided sensors (SINTEF, Norway), of area 81.6×19 mm2 anda wafer thickness of 350 m, gluedonto a mechanical support made of silicon (to avoidproblems due to differential thermal expansion) and a multilayer ceramic hybrid, 2 m thick. The sensor p-sides are segmentedinto 384 AC coupledstrips with an implant width of 32 m anda pitch of 46.5 m. Every thirdstrip is readout while the two intermediate strips are floating. The 64 d.c. coupledpads (area 1.25 × 18 mm2) of the sensor n-sides are oriented perpendicular to the strips and provide resolution in the axial direction. The two layers of sensors are separated in the radial cylindrical direction by 6 mm to give the necessary angular resolution. Cosmic rays were used to determine the intrinsic spatial resolution of the strip side. Plotting the differences between predictedhit positions andmeasuredpositions andusing a weighted average of adjacent strips, a position resolution of 28 m was obtainedby the ATHENA collaboration. This is much smaller than the straggling due to multiple scattering in the materials traversed by the pions before they reach the detector and to the uncertainty in position definition due to the bending of the tracks in the applied magnetic field. The latter dominates the overall spatial resolution in vertex determination, which is given by the ATHENA collaboration as 4mm for 1 sigma.

9.1.2. 511 keV -ray detection The -ray detector is an electromagnetic calorimeter and is a cylinder of about 16 cm in length built up from 16 rows of 12 CsI crystals each. The dimensions of the individual crystals are 17 × 17.5 × 13 mm3. Good results have been obtained with crystals of pure CsI at low temperatures. The total light output increases strongly with decreasing temperature and reaches about 50,000 photons/MeV at 80 K [245]. This increase is accompanied by a shift of the emission spectrum towards longer wavelengths which are better suited for detection by photodiodes. Photodiodes are used

instead of phototubes because of the presence of strong magnetic fields. Whilst both these effects are beneficial to detection, the strong temperature dependence requires precise temperature control of the calorimeter enclosure. The solidangle coveredby the calorimeter is approximately 2, while the conversion probability for a 511 keV -ray in 2 cm CsI is just below 25%, leading to a total detection efficiency for simultaneous detection of both ’s of about 5%. Details on the detector assembly and the read-out and trigger mechanism can be foundin [243]. A reconstruction of a typical antihydrogen annihilation event in the ATHENA detector is shown in Fig. 32.

(physics with antihydrogen) 3.1. Annihilation When antihydrogen is formed (in the absence of a neutral atom trap), it is likely to promptly (within a few microseconds) migrate to the electrode wall of the charged particle trap where it will annihilate on contact. The antiproton annihilation with nuclear matter results in the release of pions, several of which (typically two or three) may be charged. These pions are sufficiently energetic that they penetrate the walls of the vacuum chamber and other materials which may surround the trap, and can then be registered using external detectors. Positron–electron annihilation is almost exclusively accompanied by the emission of a pair of back-to-back gamma rays each with an energy close to m ce 2 = 511 keV, with me the positron/electron rest mass and c the speed of light. Over the years, a number of different technologies have been used to detect the annihilation products associated with antihydrogen (e.g. [30, 75, 81]), but we will discuss the ATHENA detector here in detail, as it provided the first conclusive detection of cold antihydrogen through temporally and spatially coincident detection of the antiproton and positron annihilations. ATHENA’s detection system had the dual capability to register the pions using a double layer silicon-strip detector, and the gamma rays with a ring of 192 CsI scintillation devices, arranged in 16 lines of 12. In ATHENA’s original work [29], the production of cold antihydrogen was first identified by isolating events where a clear antiproton annihilation vertex (see below) was accompanied by the pair of gamma rays. An entire event was reconstructed only around 0.25% of the time, principally due to the inefficiency with which the gamma rays were detected. Fortunately, ATHENA were able to quickly establish that the antiproton annihilations alone could be used as a useful proxy for antihydrogen formation [77], such that experimental work could progress without the requirement that the positron annihilation be registered. Sources of background antiproton annihilations on vacuum rest gas, as a result of transport to the electrode wall, or perhaps due to the interaction with positive ions that may be trapped with the positrons, were identified (see e.g., [82, 83]) and largely eliminated in later work. Thus, ALPHA’s antihydrogen detector was comprised solely of an antiproton imaging system. A schematic illustration of the inner section of ALPHA is given in figure 3. The antiproton annihilation point, or vertex, is reconstructed using the three-layer silicon detector shown in the figure. This device has been described in detail elsewhere [53, 84]. In brief, the instrument consists of 60 separate modules arranged symmetrically in two halves, and in three barrel-like layers, around ALPHA’s antihydrogen trap. Each module has a double-sided silicon layer, which produces a signal to register the passage of a charged pion, which deposits energy directly into the device. Reading out the positions at which each layer of the detector was struck allows the pion trajectory to be reconstructed, and the annihilation vertex to be pin-pointed. A thorough description of the event reconstruction procedures has been given elsewhere [85]. The final vertex reconstruction resolution is 7–8 mm (due mainly to pion scattering in the

material between the annihilation event and the detector: see figure 3) and the overall annihilation reconstruction efficiency is around 60% [85]. An example reconstruction of an antihydrogen annihilation is given in figure 4, along with a cosmic ray event—the latter were the main source of background in the trapping experiments and careful filtering procedures were developed to distinguish between these two types of occurrence (see [53, 85] and the discussion in section 5.1.1)

FIRST OBSERVATION OF COLD ANTIHYDROGEN BY ATHENA 2002

(**physics with antihydrogen)** 3.2. Field ionization The antihydrogen atoms produced via the three-body reaction described in section 2.3 are loosely bound, as has been summarized in various reviews (e.g., [23, 32]), and their behaviour is therefore susceptible to influence from relatively weak ambient fields. These can be both the external electric and magnetic fields of the traps and any self-field from the particles. The latter typically arises from the positron plasma in which the electric fields can be a few 10's Vcm−1 . A detailed discussion of some of the phenomena that can occur when antihydrogen is formed in a dense positron plasma has been given by Jonsell and co-workers [86]. The effects of field ionization have been noticed by most antihydrogen collaborations using nested Penning traps. Upon antihydrogen formation, some antiprotons become separated from their parent cloud after forming the neutral, which is then field ionized, leaving them axially and/or radially isolated (see e.g. [65]). Of interest here is the deliberate field ionization of the loosely bound states, as a means of monitoring the formation of antihydrogen. Field ionization, followed by detection of one or more of the liberated particles, is a standard technique in Rydberg atom physics [87]. Electric fields Fz, here as applied along the z-axis due to the presence of the strong axial magnetic field, will field ionize atoms of radial extent eFz 4 0 1 2 r ~ ( ) p (with e the unit charge and 0 the permittivity of free space)—see [87] for corrections to this simple estimate—with ρ on the order of micrometres, corresponding to binding energies in the milli-electronvolt range. This technique was pioneered in the antihydrogen field by the ATRAP collaboration [30]. A schematic of their early electrode system, together with the electrical potential on-axis and a representation of the relevant electric fields [30], is shown in figure 5. Antihydrogen travelling along the axis must first pass through an electric field located to the right of the trapped particles in figure 5, where some of the weakest bound states will be stripped. Importantly, this field also prevents antiprotons in the nested trap side well from leaking into the ionization well. The positron may then be stripped in the ionization well (and some information gleaned as to the antihydrogen binding energy [30, 31]), whereupon the remnant antiprotons can be stored, essentially for indefinite periods. Although the technique is inherently inefficient due to the limited solid angle, as the antihydrogen has to travel 3–4 cm to reach the ionization well, there is negligible background on the signal recorded. Antiprotons can be accumulated at will in the ionization well and then ejected in a narrow (~20 ms) time window to annihilate upon striking an electrode. An example is given in figure 5(c). The field-ionziation technique was also applied by ASACUSA to set an upper bound on the state of antihydrogen detected downstream of the cusp trap on their spectrometer beamline [81].

The ATRAP collaboration has developed an entirely different approach to identifying the production of an antihydrogen atom. Due to the neutrality of the produced particle, it will no longer be confined by the electro-magnetic trapping forces andcan escape into a 4 solidangle. A fraction of the produced antihydrogen atoms which escape in the axial direction then reaches a region in the apparatus where a secondchargedparticle trap has been constructedby using an appropriate set of electrodes (see Section 9.4). The electric fieldseen by the neutral particles exceeds a value of 100V/cm. Therefore, all antihydrogen atoms which were formedin (highly) excitedstates with binding energies below a certain value are fieldionizedwithin this secondtrap. The negative antiprotons remain in the trap while the positrons are ejected. All electric potentials are carefully chosen to avoidany accidental accumulation of antiprotons in this detection trap. Therefore, any antiproton annihilation detected upon releasing charged particles from this region of the apparatus should be a direct indication of the previous presence of an antihydrogen atom. For this reason the ATRAP collaboration refers to this detection methodas being “backgroundfree.” The annihilation detector itself consists of three layers of scintillating fibers surrounding the trap. This detector, while providing a high efficiency for the detection of antiproton annihilations, does not have spatial resolution andtherefore offers no capability for vertex reconstruction.

FIRST OBSERVATION OF COLD ANTIHYDROGEN BY ATRAP

- **Overcoming Background**

(ultra-low energy antihydrogen) 9.1.3. Background rejection Monte Carlo simulations by the ATHENA collaboration show that back-to-back detection of the 511 keV ’s is a powerful tool to reject background due to the conversion of high energy ’s in the material surrounding the charged particle traps in favor of true annihilations. Background could otherwise mimic an antihydrogen event by the following mechanism (see Fig. 33). Proton–antiproton annihilation produces a certain fraction of neutral pions, which quickly decay into high energy ’s. These convert in the material of the superconducting magnet coils into an electron/positron shower. The annihilation of the positrons produces a diffuse background of 511 keV ’s which can trigger temporal coincidences between two modules of the 511 keV detector. The ’s resulting from these positron showers are randomly distributed in the entire solid angle of the detector. One can eliminate this background and distinguish “golden” events from background by analyzing the relative directions of two 511 keV ’s with respect to the vertex reconstructed for an antiproton annihilation using its charged pion signals.

(ultra-low energy antihydrogen) 5.1.1. Cosmic-ray background. ALPHA utilizes a silicon vertex tracking detector to identify antiproton annihilation events. Cosmic rays striking the Earth’s atmosphere produce showers of charged particles, some of which (mainly muons) reach ground level. Muons passing through the silicon detector leave charge deposits and trigger the logic that reads out the position information from the silicon modules. The reconstruction and analysis procedure classifies sets of three hits in three layers of the detector as a single track, and extrapolates two or more such tracks to identify an annihilation vertex. The stereotypical cosmic ray event (such as that shown in figure 4)

leaves deposits in a more or-less straight line, and can be discarded. Often however, the charged particle can be deflected in the magnetic field, so that the hits do not lie along a straight line, or the particle may disintegrate, producing several tracks from daughter species. Such events can be mis-identified as antiproton annihilations, and therefore constitute an important background. To distinguish cosmic-ray events from annihilations, a set of detector data criteria ('cuts') was developed to maximize both rejection of cosmic rays and acceptance of annihilations. These criteria were made up of limits on the maximum squared residual from the best straight line fit to the hits making up the tracks contributing to the vertex, and the maximum distance from the centre of the trap. In ALPHA's work, to be accepted as an antiproton annihilation, a reconstructed vertex was required to be within 4 cm of the trap axis. In addition, when an event had three or more tracks, the squared residual from the best-fit straight line was required to be greater than 0.05 cm2 , and otherwise greater than 2 cm2 . These criteria were optimized by maximizing the statistical significance of a given number of signal events, scaled by the acceptance measured using an almost-pure sample of annihilations recorded during mixing, against a measured background on a pure cosmic-ray data set. The completed criteria reduced the cosmic-ray background to a rate of 0.022 s−1 , while retaining ~42% of antiproton annihilations. In ALPHA, the time measurement window for detecting antihydrogen atoms released from a rapid shutdown of the atom trap magnets is 30 ms, which leads to the misidentification of a cosmic ray as an annihilation once in about 1500 trials on average. 5

Trapping Antihydrogen

TRAPPED ANTIHYDROGEN
CONFINEMENT OF ANTIHYDROGEN FOR 1000 SECONDS.

- **Theory behind trapping antihydrogen**

(**physics with antihydrogen)** Trapping antihydrogen atoms is a challenging endeavour and several new experimental techniques have been devised to overcome difficulties that have presented themselves along the way. These include refinement of classical magnetic minimum atom traps, evaporative and adiabatic cooling of plasmas to reach temperatures below those achievable with electron cooling and new mixing techniques to produce lower energy anti-atoms. Additionally, new techniques such as in situ magnetometry using trapped plasmas have been developed to address some of the systematics associated with future spectroscopic measurements.

(**ultra-low energy antihydrogen)** The long-term goals of the experiments are precision studies of matter–antimatter symmetries. This most likely requires not only the production of antihydrogen at a low kinetic energy, but also the confinement of the formed neutral atoms for a sufficiently extended period of time to be able to perform precision spectroscopy. For this purpose the magnet systems used for particle confinement in the experiments have to meet two distinctly different requirements: (1) One needs to be able to confine both the negative antiprotons (and possibly electrons for cooling) andthe positive positrons in a sufficiently high magnetic field to facilitate rapid synchrotron cooling of the light particles. To achieve stable confinement of these charged particle clouds, the field ideally should be of the order of 1 T or higher and as homogeneous as possible. (2) To trap the formed neutrals

we must also apply a strong, three-dimensional gradient field which can act upon the magnetic moment of the antihydrogen atoms. In addition, one configuration should not compromise the performance of the other, as it is generally assumed that both requirements will need to be met simultaneously.

(**Antihydrogen physics)** Trapped 11 atoms are required for the highest precision antihydrogen spectroscopy experiments discussed above. Moreover, they must be cooled below 1 K in order to be trapped, and to reduce the Doppler effect from thermal motion. H atoms cannot, of course, be confined in the charged particle trap in which they were produced. However, great advances have recently taken place in the trapping of ordinary atomic hydrogen near minima of magnetically inhomogeneous fields [1771. In such cases the required restoring force comes about because the potential energy of the positron's magnetic dipole moment ,i. in field B is —~ . B. The nucleon moment is small enough to be neglected so this is essentially the potential energy of the entire atom. If ~ is antiparallel to B, the atom will be drawn to magnetic field mimima, where its potential energy is least, while if ,~is parallel to B the atom will move away from the field minimum. The so-called low-field seekers will therefore be trapped in the potential well near field minimum by such an arrangement. The depth of a trap working on this principle is limited by achievable magnetic field gradients. Fields of strength about 1 T can in fact be produced with gradients large enough to trap low-field seeking hydrogen atoms at energies up to 0.67 K (corresponding to about 55 ~eV), and this sets a corresponding limit on the temperature to which the antiprotons and positrons must be cooled before recombination can be attempted. The simplest (anti)hydrogen trap is a magnetostatic, two-coil quadrupole which can be enclosed inside a charged particle trap. The simple quadrupole trap described above is not normally used for hydrogen trapping as there is a B = 0 region which permits Majorana transitions to untrapped (i.e. highfield seeking) states. loffe-type traps, i.e. pure quadrupole or combined quadrupole—octupole magnetic traps (see, e.g., Fig. 17) seem to be satisfactory for T < 1 K antihydrogen for all experiments, because they contain no B = 0 region and have a shallow potential valley which does not induce too many H—H collisions at these very low temperatures [177, 178]. Large numbers of hydrogen atoms have successfully been confined in loffe-type traps at Amsterdam and MIT

(**physics with antihydrogen)** 4.1. Magnetic traps for antihydrogen Hydrogen (and antihydrogen) atoms possess a small permanent magnetic dipole moment m, which, in the presence of a magnetic field B, of magnitude B, has an associated potential energy U = -m · () B. 5 In free space, Maxwell's equations prohibit a static threedimensional maximum of magnetic field, though a three dimensional minimum is realizable, allowing traps for atoms with a component of m antiparallel to B to be constructed. The ground state of antihydrogen has a spin of 1/2, and so has only two possible orientations, high-field seeking and low-field seeking, both with a magnetic moment of one Bohr magneton. An additional requirement for stable trapping is that the magnetic field experienced by the atom does not significantly change during the period of the Larmor precession, 1 4 n p L e = m egB, with g here the electron g-factor. This is easily satisfied under realistic experimental conditions. The condition that an antihydrogen atom is trapped, then, is that the atom's maximum kinetic energy is less than the difference between the minimum value of U from equation (5) and the point with the lowest value of U where the atom can escape the trap (which might be a

saddle point or a material surface). The depth of the trap, and the energy of the atoms are conventionally described in units of kelvin, with the Boltzmann constant kB as an implied conversion factor to energy units. A common form of magnetic-minimum trap is the Ioffe–Pritchard configuration, as used by the ALPHA and ATRAP experiments. A novel device, the cusp trap, has been constructed by the ASACUSA experiment. Both forms of traps have the advantage that the magnetic field is purely static, and so strong fields can be produced using superconductors.

(**ultra-low energy sntihydrogen)** Once antihydrogen has formed, electrical confinement forces cease and the atom will continue along the antiproton trajectory and, unless additional confinement forces for neutral atoms are present, hit a nearby electrode andannihilate. To confine the atom the force exertedby a magnetic fieldgradient onto its magnetic moment may be used. Fig. 1 shows the Zeeman diagram for antihydrogen atoms in their electronic groundstate. This shows the separation of the atoms into so-called“low-field” (states c andd) and“high-field” seeking states (states a andb). Atoms in the low fieldseeking states can be trappedin a magnetic field minimum as long as the difference between their total magnetic energy at the “edge” of the trap to the energy at the center is higher than the kinetic energy of the atoms at the center. The “edge” of a trap for atoms up to a temperature T is therefore given by the three dimensional magnetic field contour for which (B − B0)kT , with being the magnetic moment of the atom and B0 being the magnetic fieldvalue at the trap center. States a andb cannot be trapped without invoking wall collisions, andany transitions between states c, danda, b must be carefully avoided. This requires the central fieldvalue to be non-zero since otherwise spin-depolarizing Majorana transitions would occur through mixing of states c anddwith state b at zero field. When working with hydrogen, magnetic traps are typically filled by allowing the hydrogen “gas” to fall into the potential well through cooling by inelastic collisions with residual gas atoms and the walls, a method which is probably unacceptable for antihydrogen. Also, here the magnetic trap must be superimposed upon the nested Penning trap (that is used for the recombination process) in such a way that antihydrogen formation takes place at the minimum of the magnetic well. Antihydrogen produced in high-field seeking states will quickly leave the trap volume. The atoms formed in low-field seeking states will be repelled by the magnetic barrier and trapped, if they have kinetic energies less than the well depth.

(**physics with antihydrogen)** 4.1.1. Multipole Ioffe–Pritchard traps. The prototypical Ioffe–Pritchard trap consists of a transverse multipole magnet that produces a minimum in magnetic field transverse to the cylindrical axis and two short solenoids (known as ‘mirror coils’) to produce a magnetic minimum along the axis [88]. These coils are shown in orange and red in figure 3. Near the minimum of the trap, where the magnetic field, and hence the Larmor frequency, is small, Majorana spin flips between high- and low-field seeking states can cause loss of atoms [89]. To counter this, an additional uniform magnetic field is directed along the axis. In antihydrogen experiments, this field is strong (~T) as it also serves to transversely confine charged particles in the Penning traps. A consequence of the non-cylindrically symmetric transverse magnetic field of the multipole is that it can disrupt the aforementioned charged particle confinement. In the most extreme case, particles residing outside a critical radius follow a magnetic field line that crosses an electrode surface over the length of an axial oscillation, and are immediately lost [90]. Even outside this regime,

measurements on non-neutral plasmas stored in a quadrupole demonstrated an increased rate of diffusion in the transverse direction, thus reducing the storage time and possibly resulting in heating through the release of electrostatic potential energy [91]. It is desirable, therefore, to minimize the strength of the transverse magnetic field to which the trapped plasmas are exposed. Because the latter are confined in a narrow region near the axis of the trap, this can be achieved by choosing a high-order multipole, since for a multipole of order l, the transverse magnetic field B^ ( )r scales as rl-1 . A large l reduces the magnetic field at small r, but the high gradient near the trap edge means that it is important that the current carrying windings are as close as possible to the trap boundary, or a large fraction of the trap depth is lost. Figure 6 illustrates both of these aspects, where it has been assumed that the maximum sustainable magnetic field near the coil windings (situated at RMag) is the same for each multipole order.

(**ultra-low energy sntihydrogen)** Alternatively, it has been proposedto form the atoms external to the neutral trap region andto let them drift into the magnetic well, where an appropriate RF fieldwill be appliedto change the direction of the magnetic moment [247]. Thus, high-fieldseeking atoms entering the trap will become low-fieldseekers andwill be confined in the well. This is similar, in principle, to atoms entering a Penning trap as a cold beam and being ionized inside the electric well of the trap. The trap configuration usedto confine low-fieldseeking hydrogen atoms normally consists of an arrangement of coils known as an Ioffe–Pritchard trap [248,249]. It is designed to produce a magnetic minimum at the center of the trap without having a zero-field location. Axial confinement is achieved through coaxial solenoids at either end of the trapping volume, which provide both a barrier against axial leakage andalso the non-zero fieldvalue in the center. Radial confinement is effectedby superimposing a quadrupole (or higher multipole) field over the entire length of the axial well. Ioffe–Pritchard magnetic traps have been pioneered and successfully used by the groups at MIT [250] and Amsterdam [251]. Typically trap depths of 1 K are achieved.

(**physics with antihydrogen)** 4.1.2. Cusp trap. An alternative to the Ioffe–Pritchard trap is a system of coils in the anti-Helmholtz configuration. These produce a cylindrically symmetric magnetic field, but with a zero at the minimum. Atoms will be lost via Majorana transitions here, and consequently the trapped lifetime will be reduced. In this scheme, depicted in figure 7, antihydrogen is produced in a region of stronger magnetic field, displaced along the cylindrical axis from the minimum. Low field seeking atoms tend to be focused and extracted along the axis, while high field seeking atoms are defocussed. This produces a spin-polarized beam of antihydrogen directed along the axis of cylindrical symmetry that can be used for ground-state hyperfine spectroscopy, by passing the beam through a radiofrequency cavity to induce resonant transitions between the spin states, coupled with spin-state-selective detection. An interaction and detection region placed along the axis can interact with the atoms while being outside a region of strongly inhomogeneous magnetic field, in principle allowing for high-precision spectroscopy [98]. An additional advantage of this scheme is that significant focusing and polarization of the atoms can be achieved at temperatures much higher than those needed to stably trap the atoms. ASACUSA's cusp trap is expected to produce a polarization as high as 99% at temperatures up to 5 K [99].

- **Experimental techniques used to trap and cool antihydrogen**

(**physics with antihydrogen)** ALPHA constructed an octupole (l = 4) based magnetic trap with a transverse magnetic field of 1.54 T at the inner radius of the trap (rw = 22.275 mm). The mirror coils, located 137 mm to either side of the trap centre, produced a magnetic field of 1.0 T near their centres [92]. These fields combined with a solenoidal field of 1.0 T to give a trap depth of 0.8 T, equivalent to an energy of 0.54 K kB for ground state antihydrogen. The trap depth was maximized by winding the superconducting wire directly onto the outer wall of the vacuum chamber and using electrodes with a wall thickness of less than 1 mm. Measurements of the temperature of plasmas in the octupolar field showed significant heating rates, which could be reduced by using plasmas with smaller radii [93], which was taken as a validation of the choice of the higher-order magnetic field. ATRAP initially constructed a magnetic trap using a quadrupolar (l = 2) transverse field, with a depth of 0.56 T, corresponding to 0.38 K kB, and a volume of radius 18.0 mm and length 220 mm [94]. In 2011–2014, they constructed a new generation of their experiment that allows either a quadrupolar or octupolar configuration to be selected [95]. In 2012, ALPHA constructed a second generation trap following the same geometry as the previous device, but including a total of five short solenoids spaced along the trapping region. The additional coils are intended to be used to vary the length of the magnetic trap and to cancel field inhomogeneities [96]. Both ALPHA and ATRAP have reported trapping antihydrogen [80, 97]. Key to both demonstrations was the need to de-energize the traps to allow the antihydrogen atoms to escape, annihilate and be detected. The annihilation detectors used are also sensitive to cosmic rays, which forms a background. Minimizing the length of time over which the atoms escape proportionately reduces the number of background counts, and a significant improvement in signal-to noise can be obtained. ALPHA implemented a rapid shutdown system, in which the current from the magnets was switched through a dissipative resistor network using a high speed insulated-gate bipolar transistor device. Coupled with a low inductance design for the magnets, this allowed the magnetic fields to be shut off with a decay constant of 8 ms for the mirror coils and 9 ms for the octupole. They defined a 30 ms annihilation detection window in which the trap depth had decayed to less than 1% of its original value [92]. ATRAP's original magnet, not originally designed for rapid shutdown, could be ramped off in around 1 min. However, by purposefully inducing a quench in the superconductor by heating the coils, this could be improved to around 1 s, albeit with a long recovery time required afterwards. Recently, ATRAP have constructed a new magnet, which is designed to be operated as either a quadrupole or octupole, and can be turned off in tens of milliseconds

Measurements Antihydrogen

OBSERVATION OF THE HYPERFINE SPECTRUM OF ANTIHYDROGEN
OBSERVATION OF THE 1S-2S TRANSITION IN TRAPPED ANTIHYDROGEN
RESONANT QUANTUM TRANSITIONS IN TRAPPED ANTIHYDROGEN ATOMS

- **Measurements of internal behaviour**
- **Measurements of gravitational behaviour**

Future developments

- **Overview of current achievements**
- **Projects that are being developed**
- **Possible avenues that the field could go down.**

Conclusion