Precision experiments with antihydrogen: an outlook

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Abstract. After a first generation of experiments has demonstrated the feasibility of forming - in a controlled manner - low-energy antihydrogen atoms via several different techniques, a second generation of experiments is now attempting to trap sufficiently cold atoms, or to form an atomic beam of antihydrogen atoms.

The goal of these experiments is to carry out comparative precision spectroscopy between hydrogen and antihydrogen, in view of testing the CPT theorem, either through 1S-2S spectroscopy or via a measurement of the hyperfine splitting of the ground state of antihydrogen. A related class of experiments combines techniques from these experiments with recent developments in the formation of positronium to test the gravitational interaction between matter and antimatter.

A significant number of challenges and limitations will still need to be overcome before precision measurements with antihydrogen become feasible, with the next significant milestones being either trapping of antihydrogen or the formation of a beam of antihydrogen.

1. Introduction

Precision measurements of antimatter hold promise of highly sensitive tests of CPT symmetry, as well as of a novel test of the weak equivalence principle with a new class of probe. The CPT theorem lies at the heart of much of 20th century physics, and rests on solid postulates. However, a number of extensions to the standard model have been proposed in recent years [1] that allow for the possibility of CPT violation. Specifically, a general framework has been developed [2] that parametrizes deviations from the standard model Lagrangian through CPT and Lorenz-violating terms.

Also the gravitational interaction between matter and antimatter is an open question. While numerous tests of the weak equivalence principle have been carried out, constraints derived from these tests [3] are often assumption dependent [4], and can be avoided through specifically constructed models, such as those incorporating gravivector and graviscalar components [5].

Antihydrogen is a highly sensitive test-bed for CPT, if the same spectroscopic precision as that obtained in the case of hydrogen [6, 7] can be achieved, while in the case of the gravitational interaction between matter and antimatter, it is one of the very few antimatter systems in which measurements can be envisaged (proposals have also been put forward to study two other neutral systems, positronium (Ps) [8] and most recently, muonium [9]) since their sensitivity to electric and magnetic fields excludes charged (anti)particles from such tests.

Should any asymmetry in the properties of matter and antimatter become apparent, then these tests may in turn lead to a better understanding of the origin of the baryon asymmetry of the Universe.
2. Antihydrogen formation experiments
Among a number of techniques to form antihydrogen [10], two have been focused on, experimentally implemented and studied. Both methods require prior trapping and cooling of antiprotons and positrons in Penning traps [11]. The first method [12] relies on nested Penning traps to allow antiprotons and positrons to be brought into proximity and be allowed to interact. The resulting formation [13] of antihydrogen proceeds via the three-body process
\[ e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+ \]
and leads to weakly bound states susceptible to be re-ionized both collisionally and through field-ionization. These effects significantly modify the expected dependency of the formation rates on plasma density and temperature [14], and represent a transport mechanism for antiprotons from the core of the positron plasma (assuming on-axis injection of the antiprotons into the positrons) to its surface, particularly in the case of high density positron plasmas. Such a transport mechanism is problematic for attempts to produce trappable antihydrogen, since not only does it reduce the formation rate through a rapid reduction of the available antiprotons, but in addition, the velocity of antihydrogen formed at the surface of the positron plasma will be determined by the \( E \times B \) drift of the antiproton prior to formation. According to simulations [14], the resulting antiproton energies would be in excess of the depth of achievable magnetic multi-polar traps. The same simulations also underline the importance of controlling the density of the positron plasma in this formation scheme to tune the antihydrogen velocity distribution, and thus optimize their trappability.

A second production technique [15] relies on interacting antiprotons in a Penning trap with Ps, that is produced by interacting Rydberg Cs atoms with positrons in a second nearby Penning trap. The cross section for this double-charge exchange process is lower than the three-body process, but - assuming sufficiently low-energy antiprotons - should result in low energy, and thus potentially trappable, antihydrogen atoms, given the very low momentum transfer from the (low mass with respect to antiprotons) Ps to the formed antihydrogen atoms.

Experimental evidence for production of high-temperature (and thus untrappable) antihydrogen atoms via the three-body formation process comes from a transmission measurement of antihydrogen atoms through an oscillatory electric field, which is able to field ionize specific Rydberg antihydrogen atoms [16]. The resulting velocity distribution is in good agreement with simulations [17].

3. Attempts at trapping antihydrogen
The trapping of antihydrogen is rendered difficult by two constraints. On one hand, the currently employed formation mechanisms require trapping antihydrogen atoms in the same volume in which they are produced, and in which both positrons and antiprotons must be confined, with current designs superimposing magnetic multipole traps (for the confinement of the produced antihydrogen) and nested Penning traps (for the formation of antihydrogen) [18].

On the other hand, optically trapping antihydrogen immediately after production is rendered impossible by the relatively high temperature (at best O(10 K)) of the formed antihydrogen, the excited state in which the Antihydrogen is formed, and the non-pulsed production mechanism. Even if antihydrogen were formed in the ground state, direct trapping would still require a currently unrealistically high power cw laser to provide the required cooling into the trap.

The solution chosen by the ATRAP and ALPHA collaborations is to form antihydrogen at as low a temperature as possible within a magnetic multipole that, when combined with the surrounding solenoidal fields, produces a confining potential in 3D. The requirement of confining positrons and antiprotons in the same volume imposes a minimal solenoidal field of 1T, onto which the magnetic multipole is superimposed. The depth of the potential is then sufficient to confine antihydrogen atoms with a temperature of less than 0.5 K. The defining challenge of this approach is thus that of producing antihydrogen at \( \sim K \) temperatures.
Figure 1. Nested trap for the formation of $\bar{H}$ atoms. Both positrons and antiprotons are held in Penning traps, but of opposite polarity. While the trap potentials indicated here correspond to those used in the first experiments to form antihydrogen by injecting antiprotons from the dotted well into the central well, current experiments employ greatly reduced potential values.

Although operating in a cryogenic environment, initial experiments that mixed antiprotons and positron plasmas resulted in high temperature (O(1000 K)) antihydrogen [16, 19]. A much deeper understanding of the underlying processes [20] has modified the approaches taken by ATRAP and ALPHA, who have emphasized both the initial temperature of the antiprotons and positrons, as well as the method employed to bring them into contact. ATRAP has reported [21] results on achieving ultra-cold positron and electron plasmas, with temperatures in the few K region. Recently, ALPHA has applied the technique of forced evaporative cooling to cold charged plasmas for the first time [22]. By slowly lowering the electrostatic potential well of a Penning trap containing antiprotons at a density of $\sim 10^6 \text{cm}^{-3}$, and allowing sufficient time for elastic collisions between antiprotons to scatter the highest-energy particles out of the well, a decrease of the temperature from 1000 K to antiproton temperatures as low as $(9 \pm 4) \text{ K}$ has been demonstrated (Fig. 3). Evaporative cooling is by its nature a lossy procedure: from an initial population of $\sim 50,000$ antiprotons, $(6 \pm 1)\%$ survive to the lowest temperature, corresponding to a potential depth of $(10 \pm 4) \text{ mV}$.

4. Formation of an atomic beam of antihydrogen

A number of methods [23-27] have been proposed to form a beam of atomic antihydrogen, of which two are being experimentally evaluated. In a first scheme, antihydrogen atoms are formed in an environment that almost, but not completely, confines them, allowing individual atoms to escape along a well-defined path, while in a second scheme, Rydberg antihydrogen atoms are accelerated via the Stark effect.

The standard method of forming antihydrogen atoms utilizes Penning traps, upon which if trapping is desired - magnetic bottles are superimposed. The ASACUSA collaboration has proposed two alternatives to this scheme, in which the charged components are trapped either through a Paul trap [28] or in a new type of trap, a cusp trap [24] (see Fig. 4). The latter traps positrons at the centre of a field consisting of a magnetic quadrupole and an electric octupole. The proponents expect that the total electric field of this octupole, together with the space charge of the trapped positrons themselves, will be strong enough to confine antiprotons inside the positron cloud, where the two particle species will combine to produce antihydrogen atoms.
Figure 3. From [22]: Temperature of antiprotons as obtained through evaporative cooling by the ALPHA collaboration. The model calculation in [22] is shown as solid lines. (a) Temperature vs. the on-axis depth of the Penning trap holding the antiprotons. (b) Fraction of antiprotons remaining after evaporative cooling vs on-axis well depth.

spontaneously via radiative recombination. Of particular relevance to the formation of a beam of antihydrogen atoms is the observation, in a numerical simulation, that a considerable fraction of antihydrogen atoms in low-field-seeking states formed at 5 K near the centre of the trap may be transported as a 99% polarised beam.

While the beam resulting from these methods would be continuous, it can be advantageous to know the exact moment of formation of antihydrogen atoms, both for spectroscopy with untrapped atoms, as well as to produce a pulsed beam. The formation method proposed by the AEGIS collaboration [23] relies on the interaction between antiprotons that are cooled to the lowest possible temperature by one of a number of techniques (evaporative cooling [22], electron cooling [30] or sympathetic cooling [31]) and positronium that has been laser-excited into a Rydberg state [32]. The resulting Rydberg antihydrogen atoms are then expected to have a
Maxwellian velocity distribution peaked at around 50 m/s (corresponding to 120 mK). Because these atoms are in a Rydberg state, they are amenable to being Stark-accelerated along the axis of the magnet confining the antiprotons in the Penning trap to several 100 m/s, analogously to Stark deceleration of hydrogen [33], to form a pulsed beam.

4.1. **Hyperfine splitting**

In the specific framework of the Standard Model Extension formulated by Kostelecký [2], the most sensitive test of CPT violation is not in the comparison of the 1s-2s transitions between hydrogen and antihydrogen, but rather in the comparison of the hyperfine splitting of the 1s state. In this model, the energy levels of the 1s (and 2s) hyperfine sublevels are potentially different for Hydrogen and Antihydrogen. The ASACUSA collaboration is preparing a measurement of these transitions using their proposed continuous antihydrogen beam [34] and a scheme based on a Stern-Gerlach-based apparatus. Both high-field and low-field seekers, depending on their magnetic moment, will be present in the beam; when traversing a sextupole magnet on their trajectory, the former will be defocussed, while the latter will be focused and can be directed towards a radiofrequency cavity, which is then again followed by a (sextupole) analyzing magnet. Spin-flips induced on resonance in the microwave cavity will cause the second magnet to act as a defocusing magnet, and thus reduce the flux of antihydrogen atoms arriving at a downstream detector. A simulation of the expected signal is shown in Fig. 5.

4.2. **Measurement of the gravitational interaction between matter and antimatter**

Any measurement of the gravitational fall of antihydrogen will be confronted with the thermal motion of the atoms at a temperature $T$, which must be compared to the scale of the gravitational potential energy over the distance of fall. The figure of merit is $Mgh/k_BT$. In the case of (anti)hydrogen, $k_BT/Mg$ is approximately 85 cm/mK. Attempting to measure the gravitational interaction of trapped antihydrogen thus requires cooling the atoms to $\sim 1$ mK, within a $\sim 1$ m apparatus.

However, it is possible to circumvent the requirement to trap and cool antihydrogen if, instead, it is transformed into a sufficiently cold ($\sim 100$ mK), pulsed horizontal beam. This is the approach proposed [23] by the AEGIS collaboration (Fig. 6). After having been produced and horizontally accelerated (by switching the electrodes of the Penning trap from the configuration used to confine the antiprotons into a Stark-accelerator configuration), the antihydrogen atoms freely fly through two gratings of a Moiré deflectometer before impinging on a position- and time-sensitive detector (Fig. 7). The gratings function similarly to an atom interferometer, albeit in the classical regime, and produce a periodic pattern of the antihydrogen impact points in the plane of the detector. The gravitational coupling will then be extracted from a measurement of the time-of-flight-dependent downward shift of the periodic pattern. This technique, which has been used to measure the gravitational fall of Ar atoms to $10^{-4}$ [35], will allow reaching a precision of $\sim 1\%$ with a few months of antiproton beam time, underlining the importance of the control of systematics over extended periods of time.

5. **Outlook**

Since the first formation of low temperature antihydrogen in 2002, steady progress has been made in understanding the formation mechanisms and in developing the techniques needed to produce antihydrogen that is sufficiently cold that it can be trapped, such that two experiments, ATRAP and ALPHA, are very close to achieving this goal. Spectroscopy of antihydrogen should follow closely on the heels of this expected break-through, and should rapidly lead to the first laser-cooling of trapped antihydrogen atoms, and subsequently to the first moderate precision comparisons between the spectra of hydrogen and antihydrogen, thus opening the way to a new class of highly-precise CPT tests.
In parallel, new developments and concepts have entered the field, and have prepared the technical basis to attempt to form low intensity beams of cold antihydrogen atoms, opening the possibility of a highly sensitive measurement of the HFS of antihydrogen, as well as a first measurement of the gravitational interaction between matter and antimatter.

Finally, a number of recent initiatives on further paths to produce and study antihydrogen [36, 25] or the gravitational interaction of antimatter [37, 38] are a good indication of the increasing interest that this field at the intersection between high-energy physics and atomic physics is attracting.

(Note added in proof: As hoped for, the first breakthrough - that of trapping cold antihydrogen atoms - has just been achieved: the publication [39] by the ALPHA collaboration on trapping small numbers of antihydrogen atoms in their octupolar magnetic trap raises hopes that first spectroscopy of antihydrogen will soon be within reach.)

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