Measurement of the hyperfine structure of antihydrogen

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Abstract

Among the best measured quantities in physics is the microwave transition between the ground-state hyperfine levels of the hydrogen atom at $\nu_{HF} = 1.42 \text{ GHz}$ with $\delta \nu_{HF}/\nu_{HF} \sim 10^{-12}$. A measurement of $\nu_{HF}$ for antihydrogen therefore constitutes a sensitive test of CPT symmetry. To the leading order, $\nu_{HF}(\bar{\text{H}})$ is directly proportional to the magnetic moment of the antiproton, which is experimentally known only to 0.3%. This paper describes a planned measurement of $\nu_{HF}$ for antihydrogen with an accuracy better than $10^{-6}$ using atomic beams.

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1. Introduction

Antihydrogen is the simplest atom consisting purely of antiparticles. It is an ideal laboratory for studying CPT symmetry, because its CPT conjugate system, hydrogen, is the experimentally most accurately studied atomic system. The ground-state hyperfine splitting (GS-HFS) frequency $\nu_{HF}$ in hydrogen has been measured in a classic series of experiments which began in the 1930s with relatively simple atomic beam experiments, and culminated with maser experiments in the early 1970s which ultimately achieved a relative precision of order $10^{-12}$ (for an overview, see [1]). For the antihydrogen atom, a measurement of $\nu_{HF}$ with precision equal to that achieved in the hydrogen case some 50 years ago would constitute a commensurately precise test of CPT symmetry. It may also be interpreted in terms of the gravitational interaction of antimatter.

To the leading order, the GS-HFS of antihydrogen is proportional to the spin magnetic moment of the antiproton, $\mu_p$, which is experimentally known only at the level of 0.3%. Below the level of several ppm accuracy, $\nu_{HF}$ also depends on the electric and magnetic form factors of the antiproton (cf. Section 2). The measurements of $\nu_{HF}(\bar{\text{H}})$ to a relative accuracy of better than $10^{-6}$ as discussed here will therefore yield an improvement of the value of $\mu_p$ by three orders of magnitude, and give some insight into the structure of the antiproton.
Furthermore, the only existing phenomenological extension of the standard model that includes CPT violations [2] predicts that CPT violation in the 1S–2S transition is cancelled in first order, while for the hyperfine structure it is a leading-order effect.

2. $^3$H ground-state hyperfine structure and CPT

In Fig. 1 we summarize the presently known physical quantities for the proton, the electron and the hydrogen atom, together with the precision of the theoretical values. Also shown are presently known CPT-invariant properties, which we define for a quantity $X$ as $\Delta_{\text{CPT}}(X) = (X(\text{antiparticle}) - X(\text{particle}))/X(\text{particle})$. Although relative precisions like these are dimensionless, care must be taken in comparing them, since the scale of $X$ is ambiguous in definition. Also, symmetry violations of all kinds depend on the nature of the physical observables involved. For instance, parity violation dominates only the weak interaction world and CP violation occurs only in the neutral K and B mesons. Nobody knows in which physical quantities CPT violation may appear.

![Graph](image-url)

Fig. 1. Three experimental values (large numerical letters) of the 1S–2S transition frequency, 2S–2P Lamb shift and the 1S hyperfine frequency of hydrogen are presented together with the theoretical uncertainties. Known information on CPT symmetry test is also shown ($m_e$, $M_p$: electron and proton mass, $R_p$: proton radius, $\mu_e$, $\mu_p$: electron and proton magnetic moment, $g_e$: electron $g$-factor).

The 1S ground state of hydrogen is split due to the interaction of electron spin $\vec{S}_e$ and proton spin $\vec{S}_p$ according to $\vec{F} = \vec{S}_e + \vec{S}_p$ with quantum numbers $F = 0, 1$ (total spin) and $M = -1, 0, 1$ (projection of $F$ onto the magnetic field axis). The hyperfine splitting between the $F = 0$ and $F = 1$ states of the hydrogen and antihydrogen atoms is directly proportional to both the electron (positron) and proton (antiproton) spin magnetic moments. It provides a variety of physics implications, which are unique and qualitatively different from those given by the binding energy of antihydrogen. The hyperfine coupling frequency $v_{\text{HF}}$ in the hydrogen ground state is given to the leading term by the Fermi contact interaction, yielding

$$v_F = \frac{16}{3} \frac{m_e}{M_p} \frac{1}{M_p + m_e} \frac{\mu_e^2 \alpha^2 c R_y}{N a^2 c R_y},$$

which is a direct product of the electron magnetic moment and the anomalous proton magnetic moment ($M_p$, $m_e$ denote proton and electron mass, $c$ the speed of light, $\alpha$ the fine structure constant and $R_y$ the Rydberg constant). This formula yields $v_F = 1418.83$ MHz, which is significantly different from the experimental value. This 1000 ppm discrepancy led to the discovery of the anomalous electron $g$-factor ($g_e = 2.002$).

Even after higher-order QED corrections [3] still a significant difference of 32.55 ppm remains between theory and experiment. This discrepancy was accounted for by the non-relativistic magnetic size correction (Zemach correction) [3], which depend on the electric and magnetic form factor of the proton. The Zemach corrections have been evaluated theoretically, but still today a discrepancy between theory and experiment of $(v_{\text{exp}} - v_{\text{th}})/v_{\text{exp}} = 3.5 \pm 0.9$ ppm remains [4]. A further structure effect, the proton polarizability, is only estimated to be <4 ppm [4], of the same order than the value above. The “agreement” between theory and experiment is therefore only valid on a level of ~4 ppm. Thus, we can say that the uncertainty in the hyperfine structure reflects dominantly the electric and magnetic distribution of the proton, which is related to the origin of the proton anomalous moment, a current topic of particle-nuclear physics.
A first measurement of the antihydrogen hyperfine structure will initially provide a better value for the poorly known antiproton magnetic moment ($\mu_{pp}$), the current 0.3% relative precision of which has been obtained from the fine structure of heavy antiprotonic atoms [5]. Subsequent, more precise values of $v_{HF}(\overline{H})$ will yield information on the magnetic form factor of the antiproton.

3. Measurement of $v_{HF}$ in an atomic beam

As described in detail in [1], the measurements of $v_{HF}$ in hydrogen started in the 1930s with simple Stern–Gerlach beam lines of inhomogeneous magnetic fields used as spin-state selectors, through which hydrogen atoms were transported. By inserting a microwave cavity between two spin-selectors, $v_{HF}(\overline{H})$ could be measured with a precision of $4 \times 10^{-8}$ [6,7]. Later on the precision was improved below $10^{-12}$ using a hydrogen maser, but this technique (which requires the storage of atoms in a cavity where they collide with the cavity walls) will not be possible with antihydrogen.

We therefore plan [8] to use an atomic beam setup similar to the ones used for hydrogen (cf. Fig. 2), where a sextupole magnet $S_1$ selects one spin direction, a microwave cavity flips the spin, and a second sextupole $S_2$ analyzes the spin. Sextupoles are chosen because of their ability to focus atoms from a certain solid angle and therefore to make better use of the scarce antihydrogen atoms. This approach has the advantage that the neutral antihydrogen atoms do not need to be trapped.

Antihydrogen atoms will be produced from antiprotons and positrons stored in charged particle traps. After being recombined, the $\overline{H}$ atoms are no longer confined by the traps, and leave the formation region with a velocity corresponding to the temperature of the particle clouds. Recently $\overline{H}$ formation in nested Penning traps has been achieved at the AD [9–13], and some information on production rates and conditions exist. Due to the large size of the particle clouds, in which $\overline{H}$ is produced, and the fact that these are located inside superconducting solenoid magnets, this method is not ideal for the hyperfine structure measurement. We are therefore currently investigating other formation methods like the use of radio-frequency Paul traps [8] or a cusp trap [14,15], a magnetic-bottle like structure well-known in plasma physics.

Extending our earlier work [16], extensive Monte-Carlo simulations have been made [8] on possible layouts for the different production mechanisms, including nested traps in a split solenoid that allows the particles to leave perpendicular to the solenoid axis. Assuming a Maxwellian velocity distribution with average temperature of 15 K, and realistic parameters for the sextupole magnets, we expect to transport fractions between $5 \times 10^{-5}$ and $2 \times 10^{-4}$ of all atoms formed to the $\overline{H}$ detector, without appreciable background from the annihilations products. Assuming that the reported production rates [9,11,12] can be scaled by the factor 100 higher trapping efficiency of the ASACUSA radio frequency quadrupole decelerator (RFQD) and catching trap [17], and that at 15 K the recombination proceeds dominantly via radiative recombination directly to the ground state, we can
expect to observe a count rate of typically one event per minute on resonance at the $\bar{\Pi}$ detector, enough to finish one resonance scan in one day. If the fraction of ground-state antihydrogen atoms is not large enough, it can be increased using laser-stimulated recombination [18,19].

In this atomic beam setup, the achievable resolution is given by the flight time of the atoms through the cavity. Since the double sextupole structure has a rather narrow velocity acceptance, the additional broadening from the velocity distribution will not seriously deteriorate the resolution. For an average velocity of 350 m/s and a cavity length of 20 cm, the expected width of the resonance curve is about 3 kHz corresponding to $2 \times 10^{-6}$. With enough statistics, the line center can be easily determined to better than ppm precision.

4. Conclusions and outlook

The ground-state hyperfine splitting in antihydrogen can give unprecedented accuracy for tests of CPT symmetry. The measurement in an atomic beam as sketched in this paper is feasible at the AD with the expected formation rates using the ASACUSA radio frequency quadrupole decelerator, and a letter of intent has been submitted to CERN. The measurement will improve the value of the magnetic moment of the antiproton by three orders of magnitude, and may give some insight in the internal structure of the antiproton if measured to better than $10^{-6}$. The GS-HFS will yield unique information on CPT symmetry in the hadronic sector which is qualitatively different from the one obtained by the 1S–2S laser spectroscopy.

References