Measurement of the ground-state hyperfine structure of antihydrogen

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Abstract. The ASACUSA collaboration at CERN-AD has recently submitted a proposal to measure the hyperfine splitting of the ground state of antihydrogen in an atomic beam apparatus [ASACUSA proposal addendum, CERN/SPSC 2005-002, SPSC P-307 Add.1 (2005)]. The apparatus consists of two sextupoles for spin selection and analysis, and a microwave cavity to flip the spin. This method has the advantage that antihydrogen atoms of temperatures up to 150 K 'evaporating' from a formation region can be used. Numerical simulations show that such an experiment is feasible if ~100 antihydrogen atoms per second can be produced in the ground state, and that an accuracy of better than 10^{-6} can be reached. This measurement will be a precise test of the CPT invariance.

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Motivation of the experiment

The Charge-Parity-Time reversal (*CPT*) invariance is one of the most fundamental symmetries of nature. It is a mathematical theorem which is valid for all quantum field theories used so far; however, its assumptions are not valid any more in string theory. CPT symmetry predicts that antimatter should be an exact 'mirror image' of matter, i.e. the absolute values of the mass, charge, magnetic moment etc. of a particle and its antiparticle should be equal. However, the apparent dominance of matter in the universe might indicate CPT non-conservation, therefore tests of fundamental symmetries are a current topic in both nuclear and elementary particle physics.

There are many different physical systems in which it is possible to test the CPT symmetry. One of them is the antimatter counterpart of the simplest neutral atom, the antihydrogen ($\overline{\mathrm{H}}$), which consists of an antiproton ($\overline{\mathrm{p}}$) and a positron. The 1s ground state of hydrogen (antihydrogen) is split due to the interaction between the electron (positron) spin $\vec{S}_e$ and the proton (antiproton) 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 states with quantum numbers $F = 0$ (singlet state) and $F = 1$ (triplet state) have different energies even at zero external magnetic field.

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The frequency ν_{HF} of this ground state hyperfine splitting (GS-HFS) has been measured very precisely for hydrogen; however, it has not been measured yet for antihydrogen, since the first few low-energy $\overline{\mathrm{H}}$ atoms have been produced just a few years ago by the ATHENA [2] and the ATRAP [3] experiments. The splitting frequency in hydrogen (antihydrogen) is proportional to both the electron (positron) and proton (antiproton) spin magnetic moments. The antiproton spin magnetic moment $\mu_{\bar{\mathrm{p}}}$ is known to a precision of only 0.3%, therefore a measurement of ν_{HF} for antihydrogen with a precision of only 10^{-6} can already lead to an improvement of the value of $\mu_{\bar{\mathrm{p}}}$ by three orders of magnitude.

In the recent years, the group of V.A. Kostelecky has developed an extension of the standard model of elementary particles that includes both CPT violating and Lorentz invariance (LI) violating terms in the Lagrangian of the quantum field theory [4]. The parameters introduced by this theory have a dimension of energy (or frequency) i.e. they have an absolute magnitude rather than relative difference. Therefore within the framework of this theory, it is not necessary to measure the 1.42 GHz GS-HFS frequency to 10^{-18} precision to be competitive with the oft-quoted 'most sensitive CPT limit' of $|m_{K^0} - m_{\overline{K}^0}|/m_{K^0} < 10^{-18}$ [5]. This is because in terms of absolute precision, this only corresponds to $|m_{K^0}c^2 - m_{\overline{K}^0}c^2|/h < 1.2 \times 10^{-5}$ Hz, thus the measurement of the antihydrogen GS-HFS to a precision of only 10^{-4} ($\Delta\nu \sim 100$ kHz) can already lead to an absolute sensitivity to CPT violating effects as good as the K^0–$\overline{K}^0$ comparison.

Proposed experimental method

The ground state hyperfine splitting frequency of hydrogen has been measured to a precision of about 10^{-12} using a maser spectroscopy method [6]. Unfortunately, maser spectroscopy is probably unfeasible at the moment for antihydrogen, because the $\overline{\mathrm{H}}$ atoms would not be trapped in the maser cavity but collide with its walls and annihilate. Measuring ν_{HF} in a neutral atom trap by microwave spectroscopy would have limited accuracy due to the largely inhomogeneous magnetic field of such traps.

Therefore we plan to use a method similar to classical atomic beam (Stern-Gerlach type) experiments. This includes *i)* a sextupole (i.e. inhomogeneous) magnetic field to select the spin of the $\overline{\mathrm{H}}$ atoms, *ii)* a microwave cavity to induce spin-flip transitions when tuned to ν_{HF}, and *iii)* a second sextupole field to analyze the spin state of the atoms.

A schematic view of the spectrometer is shown in Fig. 1. The $\overline{\mathrm{H}}$ atoms emerging from a recombination trap will pass through a sextupole magnet, where they will experience a radial force $F_r = 2C\mu r$ acting on their magnetic moment μ, with C being a constant determined by the maximum field strength and the inner diameter of the magnet.

Depending on the sign of their magnetic moment, the four hyperfine states of the $\overline{\mathrm{H}}$ atoms can be divided into two pairs (see Fig. 2): 'high-field seekers', which will move towards regions of higher magnetic field and thus will be defocused, and 'low-field seekers', which will be attracted towards the sextuple axis and thus will be focused onto a microwave cavity. The focused atoms will then pass through a second sextupole, which will again focus them onto an antihydrogen detector. However, if a $\overline{\mathrm{H}}$ atom in e.g. the $(F,M) = (1,-1)$ low-field seeker state is converted into the $(0,0)$ high-field seeker

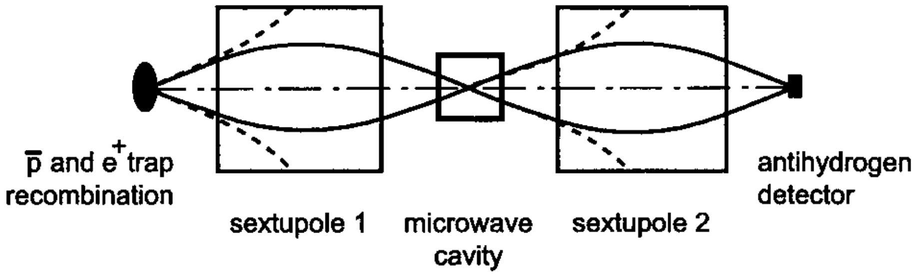

FIGURE 1. Schematic view of the proposed atomic beam spectrometer with the antihydrogen source, the two sextupole magnets and the microwave cavity. The trajectories drawn with solid lines represent $\overline{H}$ atoms in low-field seeker states, while the dashed lines represent $\overline{H}$ atoms in high-field seeker states.

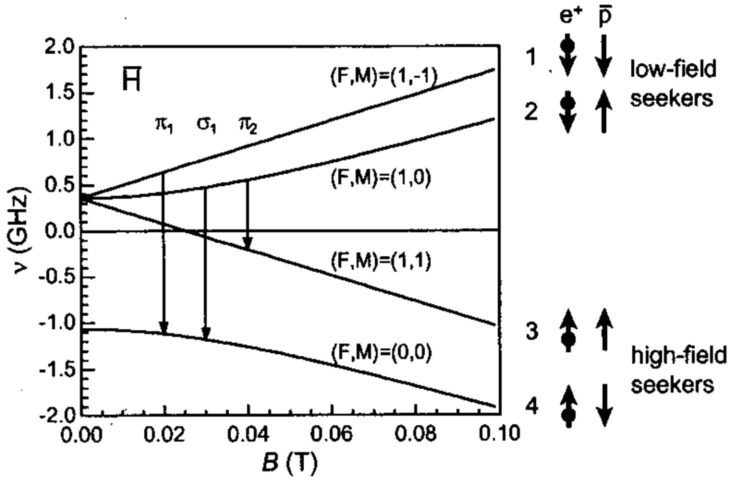

FIGURE 2. Frequencies (i.e. energies) of the four hyperfine states of antihydrogen as a function of the external magnetic field B. The transitions observable with the proposed method are also drawn.

state by a microwave field of appropriate frequency in the cavity, then the atom will be defocused and will not reach the detector. Thus the on-resonance count rate in the detector will drop from the constant off-resonance count rate.

The atomic beam method has the advantage that it can work with relatively high-temperature (up to 150 K) atoms, while trapping for e.g. 1s-2s laser spectroscopy would require ultra-cold (< 1 K) atoms.

The 'conventional' way to produce antihydrogen is to use a nested Penning trap [7]. However, such a trap produces $\overline{H}$ atoms in a relatively large volume, and the access to the center of the trap is quite limited. Therefore we are developing two new $\overline{H}$ recombination traps, which are better suited for the atomic beam method: a two-frequency Paul trap, and a cusp trap. A detailed description of these can be found in [1].

Monte Carlo simulations

Simulations using the GEANT4 toolkit [8] have been carried out to estimate the expected count rates and experimental resolution. Taking the observed antihydrogen

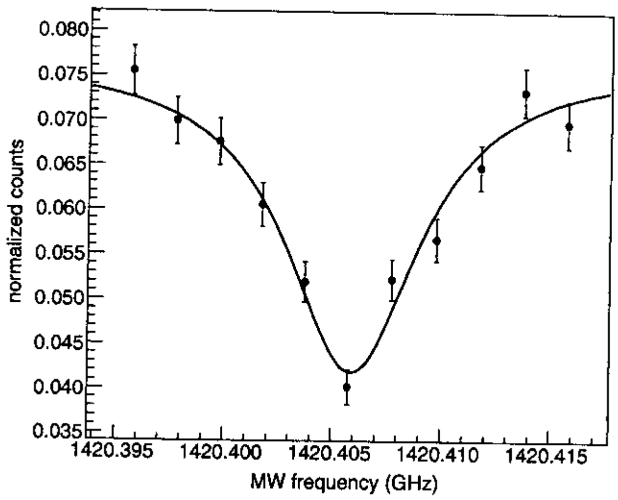

FIGURE 3. Simulated microwave resonance curve of the $(F,M) = (1,0) \rightarrow (0,0)$ transition. The FWHM of the fitted Lorentzian function is ~7 kHz, while the uncertainty of the center value is 0.25 kHz. The spectrometer geometry used in this simulation is not yet optimized.

production rate of ATHENA and scaling it with the factor ~100 more efficient trapping demonstrated using our Radio Frequency Quadrupole Decelerator (RFQD), we can expect a production rate of 200 $\bar{\mathrm{H}}$/s. The Monte carlo simulations showed that the total transmission efficiency of the spectrometer will be 5–20 $\times 10^{-5}$, thus the detection rate at the antihydrogen detector will be 0.5–2 $\bar{\mathrm{H}}$/min.

Figure 3 shows a simulated microwave resonance curve of the $(F,M) = (1,0) \rightarrow (0,0)$ transition. Based on the simulations, we can expect a resonance width of a few kHz, while the center of the resonance can be determined with a precision below 1 kHz, which corresponds to a relative precision of $< 10^{-6}$.

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