

An atomic hydrogen beam to test ASACUSA's apparatus for antihydrogen spectroscopy

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Abstract The ASACUSA collaboration aims to measure the ground state hyperfine splitting (GS-HFS) of antihydrogen, the antimatter counterpart to atomic hydrogen. Comparisons of the corresponding transitions in those two systems will provide sensitive tests of the CPT symmetry, the combination of the three discrete symmetries charge conjugation, parity, and time reversal. For offline tests of the GS-HFS spectroscopy apparatus we constructed a source of cold polarised atomic hydrogen. In these proceedings we report the successful observation of the hyperfine structure transitions of atomic hydrogen with our apparatus in the earth's magnetic field.

Keywords Antihydrogen · Atomic hydrogen · Ground state hyperfine structure

1 Introduction

The hydrogen (H) atom is one of the most precisely investigated systems in physics. For instance, the 1s-2s transition has been measured with a precision of $< 10^{-15}$ [1] and the GS-HFS is known to a level better than 10^{-12} [2].

As a consequence high sensitivity to CPT violations can be achieved by measuring the same transitions in antihydrogen \bar{H} [3], since CPT invariance predicts that the properties of particles and their antiparticles are exactly the same or exactly the opposite.

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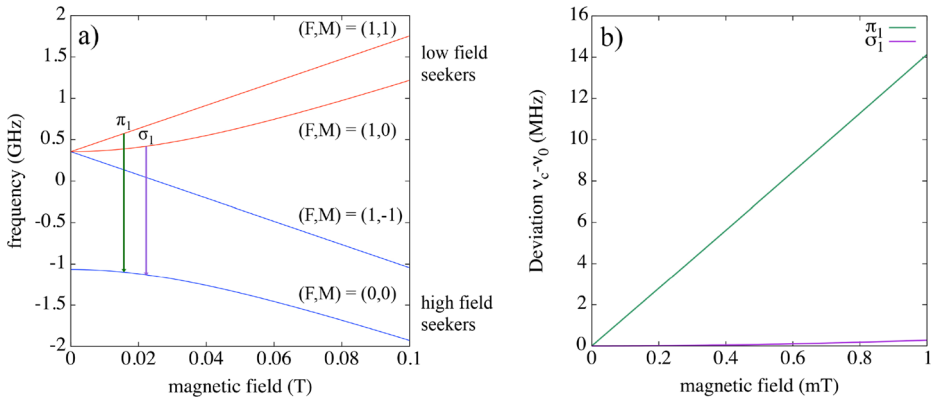


Fig. 1 **a)** Breit Rabi diagram for hydrogen: The interaction of the electron and the proton can be described with the quantum numbers F , the total spin, and M , the projection of F . $(F, M) = (0, 0)$ is a singlet state and $(F, M) = (1, -1)$, $(1, 0)$, $(1, 1)$ a triplet state. The transition from $(F, M) = (1, 1)$ to $(0, 0)$ is called π_1 and the transition from $(F, M) = (1, 0)$ to $(0, 0)$ is called σ_1 [11]. **b)** Deviation of π_1 and σ_1 transition frequencies (ν_c) in magnetic field. The π_1 transition shifts faster than the σ_1 transition and therefore this transition is more sensitive to magnetic field inhomogeneities.

The antihydrogen group within the ASACUSA collaboration focuses its experiments on testing the CPT symmetry by comparing the GS-HFS of the hydrogen and antihydrogen atom [4]. During the Long Shutdown 1 period at CERN antiprotons could not be delivered and therefore no $\bar{\text{H}}$ s could be produced. Hence we constructed a source of cold polarised atomic hydrogen to test and characterise components of the spectroscopy beam line, that will be used for the $\bar{\text{H}}$ -HFS measurement. The main two components are a radio frequency (RF) cavity to induce spin flips and a superconducting sextupole magnet used as a spin state analyser.

2 Method

HFS transitions can be directly measured by the magnetic resonance technique invented by Rabi in the 1930s [5]. The best measurement of the hydrogen GS-HFS using Rabi's method achieved a precision of 4×10^{-8} [6, 7]. Higher precision has been reached in maser experiments [8, 9], however, this method is not directly transferable to $\bar{\text{H}}$. Rabi's method is based on spatial separation of spin states in external magnetic field gradients. As can be seen in Fig. 1, the triplet splits up into two states $(F, M) = (1, 1)$, $(1, 0)$ that increase their energy in presence of an external magnetic field, while the third triplet state $(F, M) = (1, -1)$ lowers its energy like the singlet state $(F, M) = (0, 0)$. As a result, in two states the atoms experience a force toward higher magnetic fields (high field seekers) while in the other two states the atoms experience a force toward lower magnetic field (low field seekers).

A Rabi type experiment employs the following main components as identified in Fig. 2:

(1) a B field gradient to generate a spin polarised beam, (2) an oscillating B-field to drive spin flips, (3) a second B-field gradient to select not flipped spins, and (4) a detector. By

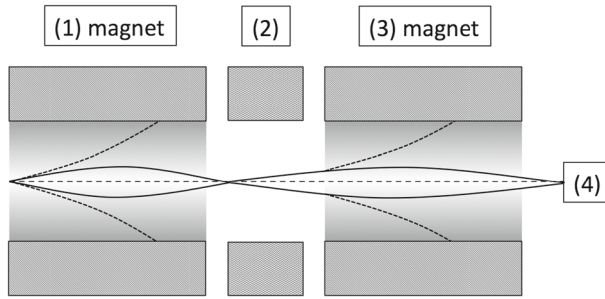


Fig. 2 Illustration of the Rabi experiment [5]: In the magnet (1) a beam of hydrogen atoms is polarised via Stern–Gerlach separation. In the setup described in this paper, sextupole magnets are used for the separation. The solid lines represent the low field seekers, the short dashed lines represent the high field seekers which are deflected, and the long dashed line shows the beam centre. In section (2) an oscillating microwave field with a frequency of about 1.42 GHz induces spin flips. In section (3) a second magnet analyses the beam. If spin flips occur, low field seekers are converted into high field seekers and therefore a drop in counting rate should be seen at the detector (4)

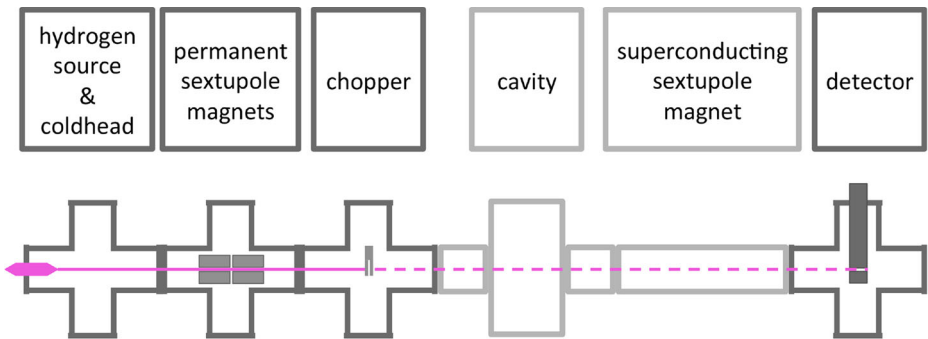


Fig. 3 H-Beam line: atomic hydrogen is formed in a plasma and then cooled with a coldhead. Sextupoles polarise the beam by sorting out the high field seekers. A chopper modulates the beam for the usage of background suppression with a lock-in amplifier. In the cavity spin flips can be driven. The superconducting sextupole magnet analyses the spin states and finally a quadrupole mass spectrometer detects the beam

scanning the frequency of the oscillating B-field the number of spin flips will vary, leading to a drop in count rate on the detector when spin flips are occurring.

3 Experimental setup

The aforementioned main components of a Rabi-type experiment are used in our \bar{H} and H experiments. In the \bar{H} experiment the polarised \bar{H} beam will emerge from a cusp trap, where the mixing of \bar{p} and e^+ takes place [4]. Spin flips are induced in a strip-line cavity with a central frequency of 1.42 GHz and a Q-value of about 100 [10]. A superconducting sextupole magnet (Tesla Engineering), with a maximum pole field of 3.6 T selects the atoms in its field gradients, by focussing low field seekers and defocussing high field

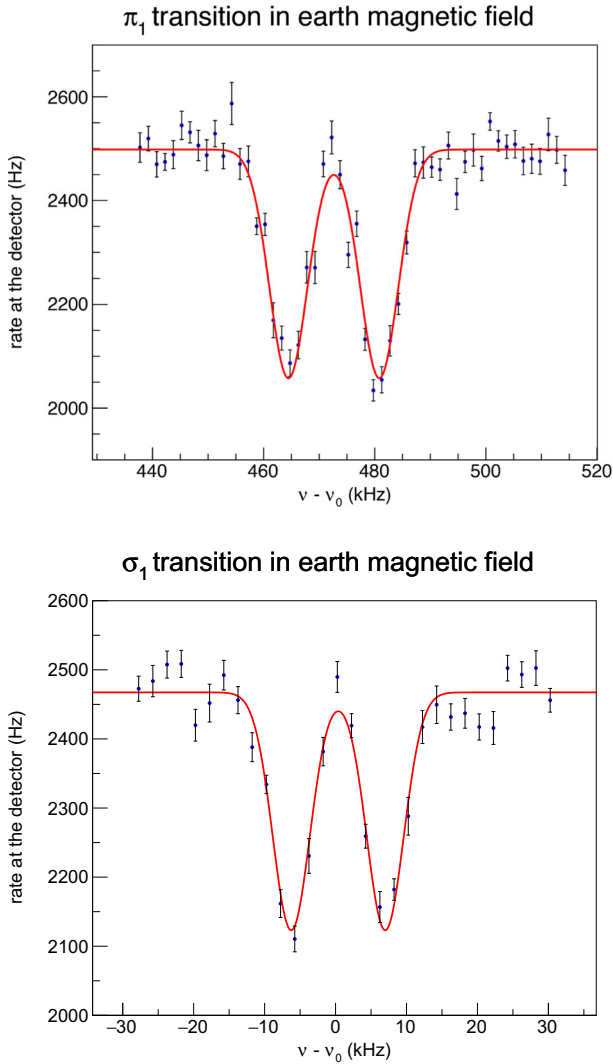


Fig. 4 π_1 and σ_1 transitions measured in the earth magnetic field with our spectrometer. The measured resonances were fitted with a double gaussian function. From the fit, we obtain the standard deviation for the single gaussian of the double gaussian function and the centre frequency

seekers. \bar{H} events are counted afterwards in an annihilation detector downstream of the superconducting magnet.

Atomic hydrogen, on the other hand, is produced by dissociation of molecular hydrogen in a microwave driven plasma contained in a pyrex glass cylinder (see ref. [12]). The atoms enter a vacuum chamber through a small orifice in the pyrex cylinder and a PTFE tubing which is kept at cryogenic temperatures in order to cool the beam to typically 50 K. The beam is polarised by using permanent sextupole magnets that have an inner diameter of 1 cm, a length of 6 cm, and a maximum pole field of 1.3 T. The same components for spin flipping and subsequent spin state selection are used for both, the H and \bar{H} experiment. To

Table 1 Results for π_1 and σ_1 transitions: First column: transition name. Second column: the centre frequency minus literature value. The errors are statistical and come from the fit. Third column: standard deviation (stdev.) of a single gaussian from the fit function. Fourth column: magnetic field calculated with Breit-Rabi formula using centre frequency of the fit. The error is gained from error propagation. Fifth column: the measured magnetic field

transition	$\nu_c - \nu_0$ (Hz)	stdev. of single gaussian (Hz)	calculated magn. field (μT)	measured magn. field (μT)
σ_1	379 ± 102	2606 ± 107	37 ± 5	37 ± 4.2
π_1	472636 ± 95	3405 ± 92	33.770 ± 0.007	

detect the H beam we use a MKS Microvision 2 quadrupole mass spectrometer (QMS). Figure 3 illustrates schematically the beamline.

4 Results and discussion

In the presence of a static magnetic field such as the earth magnetic field the frequency for a π_1 and σ_1 transition shift towards higher frequencies as can be seen in Fig. 1. The π_1 transition is more sensitive to field changes and inhomogeneities than the σ_1 transition.

We were able to observe π_1 and σ_1 transitions without any magnetic shielding as can be seen in Fig. 4. The microwave cavity was driven with a Rohde and Schwarz SML02 synthesiser referenced to a Stanford Research FS725 Rb oscillator. The microwave signals were amplified by a Mini-Circuits ZHL-10W-2G(+) amplifier and here typically 1.3 W power was needed to drive a spin flip. The frequency was scanned by changing the synthesiser frequency and keeping the power constant.

The resonances in our cavity have a double peak structure. This line shape of the resonances is a consequence of the oscillating magnetic field inside the cavity that drives the spin flips. The standing waves have a sine distribution in beam direction and therefore at centre frequency we observe a maximum in counting rate, whereas at the side lobes we drive the spin flips.

The measurements for each resonance scan took a few hours. We obtained the signals with a lock-in amplifier that used the modulated signal of the chopper and the signal from the mass spectrometer. The rate we observed is therefore the detected rate of the beam. We fitted the data with two gaussians which gave a value for the centre frequency ν_c (see Table 1 for the fit results). For the π_1 transition the deviation $\nu_c - \nu_0 = 472636 \pm 102$ kHz, for the σ_1 transition $\nu_c - \nu_0 = 379 \pm 95$ Hz. The errors are purely statistical and come from the fit. From the fit we also obtain the standard deviation for a single gaussian of the double gaussian function. This quantity is approximately a third bigger for the π_1 transition. This is a consequence of the sensitivity for π_1 which broadens the resonance. The magnetic field was measured with two Bartington Mag-03IE1000 flux gates mounted on the outside of the cavity body on the upstream and downstream side. Due to magnetic field inhomogeneities the two sensors deviated from each so that we can only estimate the magnetic field inside the cavity from the average and deviation of two measured values which gives a magnetic field of $37 \pm 4.2 \mu\text{T}$. Using the Breit-Rabi formula one can also calculate, with the values from the centre frequency, the magnetic field that was present during the measurement. The values are also given in Table 1 and are in agreement with the measured ones.

5 Conclusion and outlook

In this work we presented the first successful observation of both σ_1 and π_1 transitions obtained in our setup in the earth's magnetic field, without using any magnetic shielding. The measurements are a clear indication that Majorana spin flips, described in [13] are not a serious problem for our method. The values of the measured HFS frequencies agree within their uncertainty with those calculated from the Breit-Rabi formula using the measured magnetic field. The observed line width of 4×10^{-6} and the statistical precision of the line centre of 10^{-7} promises to enable us to determine the hydrogen HFS with significantly higher precision by applying well defined and characterised external magnetic fields and performing systematic studies of their effects.

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