Prospects for Lorentz and CPT tests with hydrogen and antihydrogen

Summer Student Report

by

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As a summer student for 13 weeks in the ASACUSA-CUSP collaboration, under the supervision of Chloé Malbrunot, my project consisted in a first part on the theoretical treatment of Lorentz and CPT violation in hydrogen & antihydrogen in the framework of the Standard Model Extension SME and in second part on experimental measurements on a hydrogen beam.

1 CPT symmetry

Antimatter is the mirror image of ordinary matter. There is an antiparticle for every particle. If CPT (the combination of Charge, Parity and Time symmetries) is conserved particles and antiparticles have the same properties, e.g. mass and same but opposite charge. But since no primordial antimatter in the universe has been detected so far, antimatter appears not to be the perfect mirror image of ordinary matter. This triggers among others searches for violation of the CPT symmetry

2 ASACUSA

At CERN a proton beam accelerated by the Proton Synchrotron to an energy of 26 GeV is targeted onto a metal block to produce pairs of protons and antiprotons from pure energy. The antiprotons are directed towards the Antiproton Decelerator (AD) and are decelerated to an energy of 5.3 MeV before they are injected to various experiments. Among those, the ASACUSA-CUSP (**A**tomic **S**pectroscopy **A**nd **C**ollisions **U**sing **S**low **A**ntiprotons) collabor-

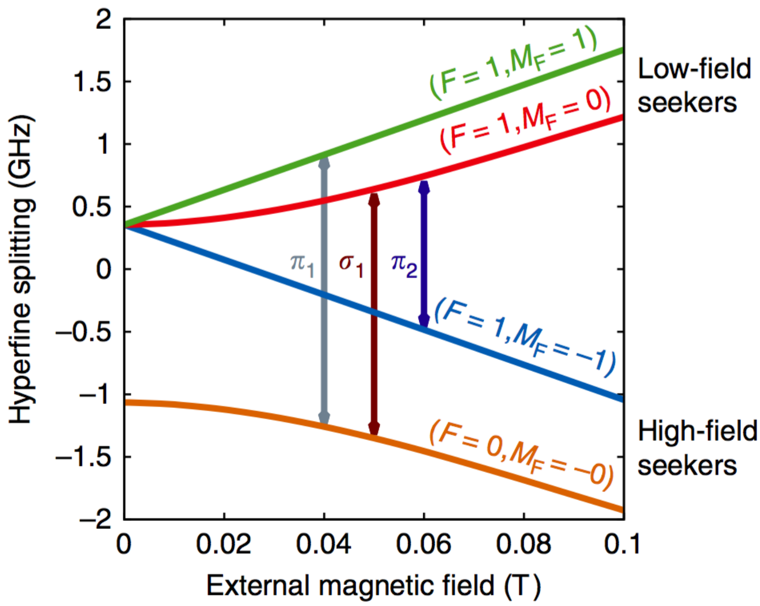

Figure 1: GS-HFS in hydrogen. The Breit–Rabi diagram shows the energy levels in ground-state hydrogen as a function of the strength of an external magnetic field. The four hyperfine states separate into a singlet state and a triplet state, which exhibit different Zeeman shifts. The states with a positive or negative slope are named low- or high-field seekers, respectively. Three possible hyperfine transitions between lfs and hfs are denoted by arrows [3].

ation's main goal is to measure the ground state hyperfine splitting of antihydrogen.
To synthesize antihydrogen the antiproton needs to capture a positron. In order to do that the antiprotons are gathered in the CUSP trap and merged together with positrons obtained by a radioactive source. In this way antihydrogen is formed which can be spectroscopically examined.
The interaction between the magnetic properties of the antiproton and the positron splits the energy levels. This is called "hyperfine structure". Interaction with an external magnetic field creates additional splitting in those energy levels. In particular one distinguishes between low-field seekers (lfs) on the one hand and high-field seekers (hfs) on the other. Hydrogen and antihydrogen atoms within one of these states are attracted towards high magnetic fields or low magnetic fields respectively.
The hyperfine transition in the absence of a magnetic field is the well known 21 cm line, equivalent to a transition frequency of $\approx 1.42\,\text{GHz}$. Therefore a microwave cavity that is resonant at this frequency can be used to induce transitions between those states. With a cavity with a few MHz bandwidth, and with a few Gauss external field, the ASACUSA collaboration can measure both the π_1 and σ transitions, see fig. 1.
In order to detect the transition (from a lfs to a hfs), a sextupole magnet is used to defocus hfs states. Therefore, as soon as the frequency is on resonance with the energy splitting, a dip in the count rate is measured. Due to the strip line geometry of the cavity the resonance arises as a double dip, so that the resonance frequency appears as a local maximum, see fig. 2.
A second and analog experiment has been prepared that purely examines hydrogen obtained by electrolysis of ordinary water. To separate the H_2-molecule it is exposed to a microwave field where hydrogen plasma is produced. The spectroscopy is performed in the same way as in the antihydrogen setup.

3 Standard-Model Extension SME

If CPT-symmetry is conserved the energy spectrum of antihydrogen and hydrogen should be the same. A difference would be a clear sign of CPT violation. A consistent framework which parametrizes possible Lorentz and CPT violation within a quantum field approach has been developed by Kostleský and collaborators [6, 1, 5].
During the first part of my project I studied articles of Kostelecký and coworkers concerning the Standard-Model Extension (SME) in order to assess the sensitivity of ASACUSA's hydrogen and antihydrogen experiments to CPT-violating fields within this model. In this model Lorentz and CPT-violating terms are added to the Standard-Model Lagrangian [7]. They can be regarded as arising from constant background fields [2]. The expression of those fields in the laboratory system leads to coefficients that transform under rotations. These coefficients would cause a shift of the hyperfine levels. In principle 72 SME-coefficients are involved in the hydrogen hyperfine splitting. 48 of them have been already constrained to high precision

(mHz) by a maser experiment measuring the sidereal time dependency of the frequency induced by the Earth's rotation [4]. For ASACUSA it is possible to put bounds on the remaining 24 coefficients for hydrogen by measuring the resonances with inversed directions of the static magnetic field. I estimated which orientation and magnitude is most appropriate to best constrain those 24 coefficients.

4 Prospects for constraining CPT violation on hydrogen

ASACUSA's hydrogen apparatus reached an unprecedented precision in a beam of the order of 3 ppm on the σ-transition [3] and can be used in its own to constrain CPT violation. In

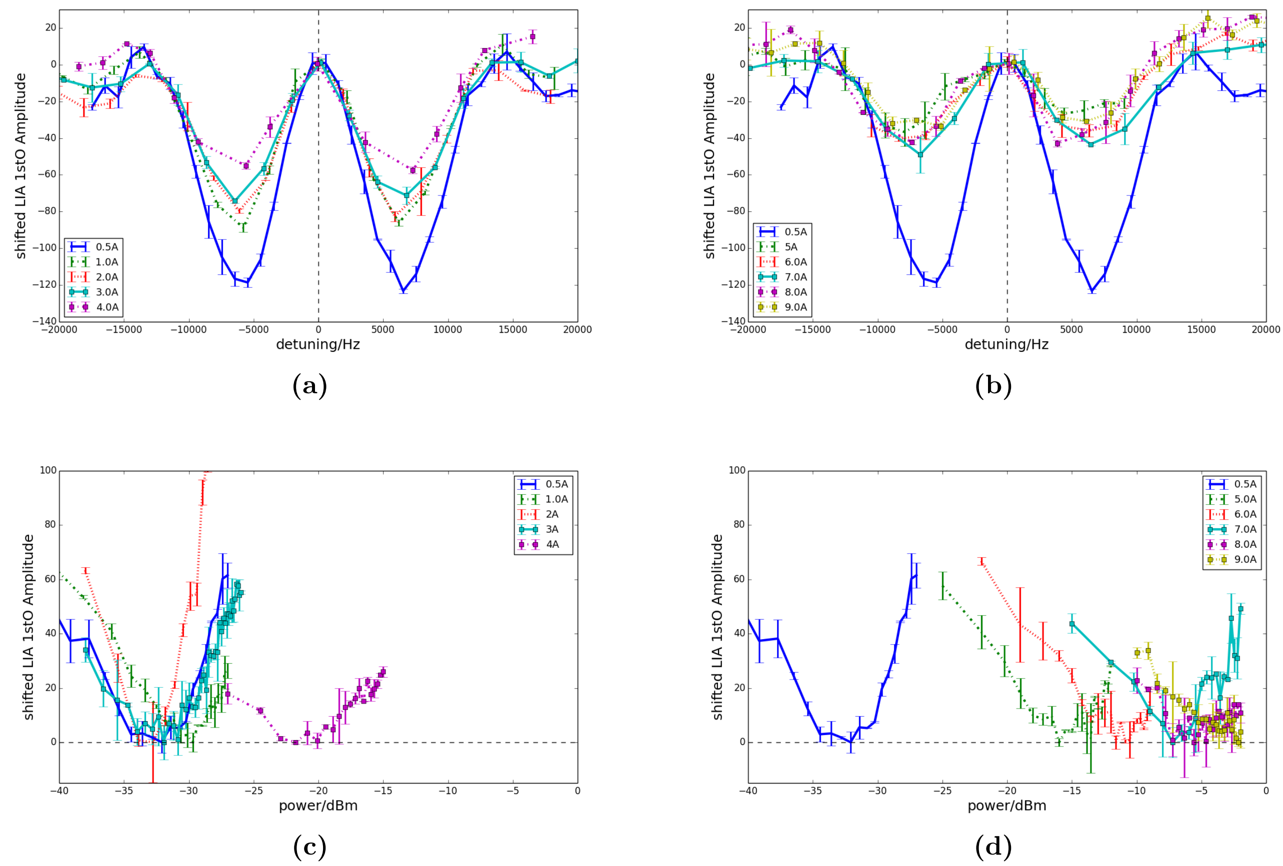

Figure 2: Characterization of the cavity at ASACUSA's hydrogen beam. (a), (b) show the π_1-resonance of hydrogen under variation of the coil current. The static magnetic field is proportional to the coil current with the scaling factor of $\approx 0.2309\frac{\mathrm{mT}}{A}$. The resonances are centered relative to the resonant frequency of about 1.42 GHz. A tuning fork chopper modulates the beam to have a noise corrected signal. This is fitted to a Fourier series where the first order amplitude appeared to be a proper beam signal.
For a fixed frequency chosen as the lower minimum of the π_1-resonance, the power scans (c) and (d) show how the beam signal alters under variation of the oscillating magnetic field power. The lines connecting the data points are there to guide the eye.

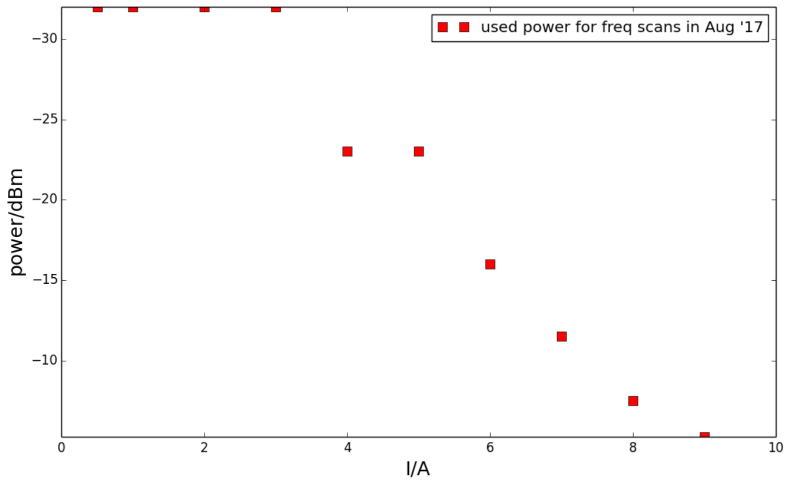

Figure 3: Power of the static magnetic field used for the frequency scans in fig. 2. To drive the π_1 transition at a given coil current both, the frequency and the power of the oscillating magnetic field, have to be chosen properly. Two distinct measurements need to be done to get those values. For each coil current I firstly scanned the frequency. Hence the lower minimum could be chosen for the power scan afterwards. Except for the frequency scan at 4 A, where I have chosen the power of −23 dBm that emerged as minimum in the particular power scan, I did not repeat the frequency scan with the appropriate power. I just estimated the power for the frequency scan by the minimum of the power scan measured at the former coil current.

the second part of my summer studentship I performed measurements at the hydrogen beam apparatus on the π_1-transition.

Since the model predicts that the σ-resonance is insensitive to SME, it can be used as a reference to maintain the same absolute value of the static magnetic field after its inversion. Thereby it is necessary to apply high field strength to have a large precision because the σ-resonance is second order dependent in the magnetic field strength. For the intended magnitude of the static magnetic field the cavity needed to be characterized. By looking at the π_1-resonance I scanned the frequency and power of the oscillating magnetic field for various static field strengths, see fig. 2 (a) and (b). At higher static magnetic fields, the transition frequency increases. As the transition is driven away from the resonance frequency of the cavity, the power needed to drive the transition increases. The optimal power arises as a minimum in the power scan, fig. 2 (c) and (d) and fig. 3.

Additionally I started to measure the resonances for inversed directions of the static magnetic field.

5 Conclusion and outlook

In conclusion I summarized the main ideas of the SME and how it affects the hyperfine states of hydrogen and antihydrogen. I understood which SME-coefficients still need to be constrained

and how the magnetic field should be chosen. Furthermore after characterizing the cavity I could start with measuring the π_1 and σ- transitions for different field directions and different field strengths.
Based on the characterization of the cavity at the hydrogen beam the measurement of the π_1- and $\sigma-$resonances can be continued for inversed magnetic field orientations. Unfortunately I had to deal with software problems and a defective heater that had to be replaced. That is why I did not have enough time to analyze all data. The presented scans only show data of the first run. A better quantitative analysis needs to be done to take into account the data of the second and third run.
The antihydrogen appliance is so far limited in its precision to the low rate of antiatoms. But as soon as it reaches the intended precision of $\lesssim 1$ p.p.m analogous measurements may give first constraints of the SME coefficients on antihydrogen.

6 References

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