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The ASACUSA hydrogen hyperfine structure measurement

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Motivation

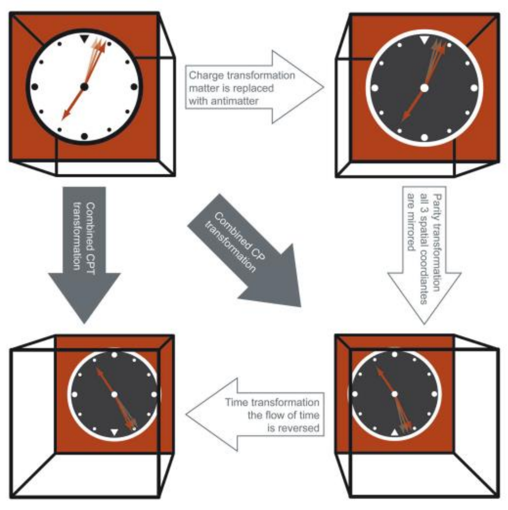
CPT-Theorem:
Particles and antiparticles have exactly same or opposite properties (e.g. mass, lifetime, magnetic moment, el. charge).

Matter-Antimatter-Discrepancy:
After Big Bang same amount of matter and antimatter, but today's universe is made of matter.

Possible solution in CPT-invariant QFT (Sakharov conditions):

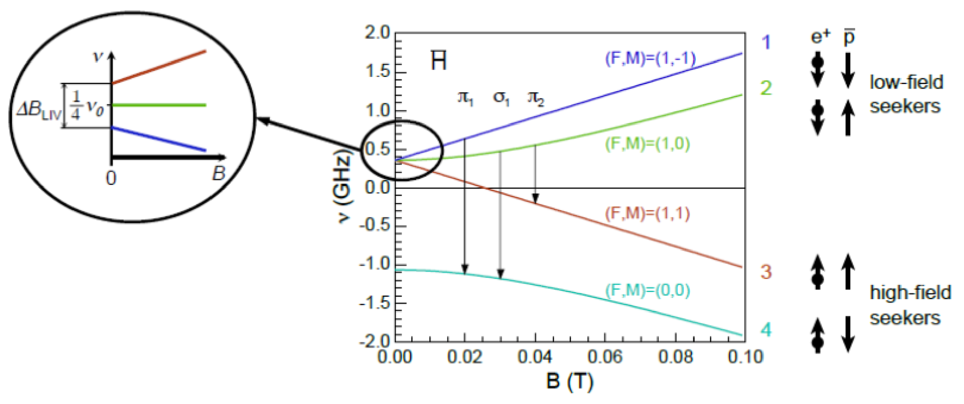
- C & CP violation
- Baryon number violation
- Interactions out of thermal equilibrium

Standard Model Extension: (SME)
Theoretical framework for systematic search of CPT- & lorentz-violation.
Adding additional terms to the SM-Lagrangian.



Symbolic illustration of the CPT-transformation [1].

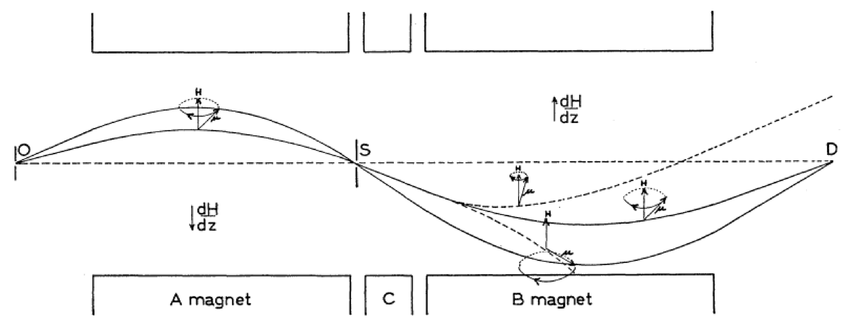
Hyperfine Splitting:
SME can change energy levels of ground-state hyperfine structure (GS-HFS) in antihydrogen.
Can be measured by Rabi spectroscopy (principle see at experiment).



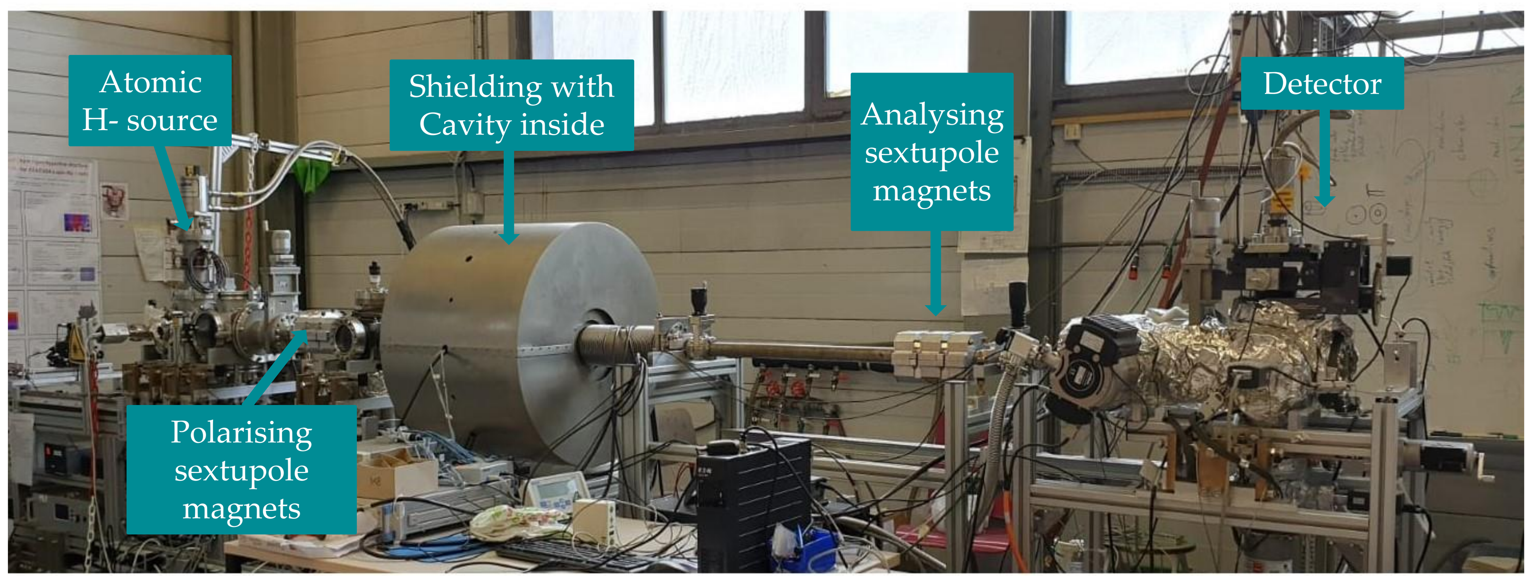
Breit-Rabi diagram of Antihydrogen GS-HFS in an external static B-field and the possible zero-field lift of degeneracy of the SME (left circle). The transitions of interest are the σ_1- and π_1-transitions, which turn low-field seekers (LFS: states having lower energy at lower B-field) to high-field seekers (HFS: states having lower energy at higher B-fields) [2].

Experiment

The experiment is in principle a Rabi-experiment and is tested with a hydrogen beam.

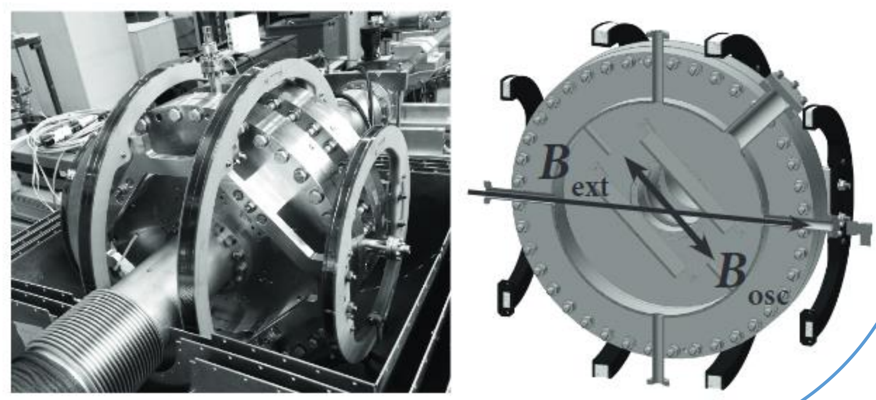


Particles coming from a source O get polarised in a B-field gradient (A). Spin flips are induced by an oscillating B-field perpendicular to a static B-field (C). Spin flipped particles are deflected by B-field gradient (B). At transition frequency a drop in intensity is observable at detector (D) [3].



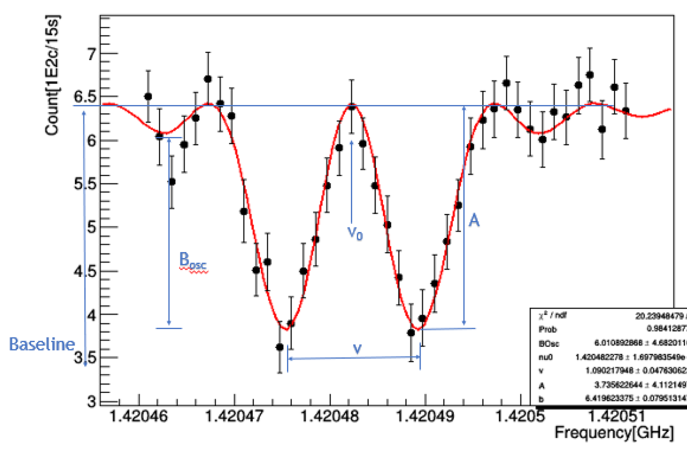
Photography of the hydrogen beam experiment [2].

Cavity (left) and B-field configuration in the cavity (right): σ_1-transition can be induced by parallel configuration of the oscillating and static B-field; π_1-transition is induced by perpendicular fields. The cavity can induce both transitions because of a 45° arrangement of the static and oscillating fields.



Evaluation with 2-level calculation

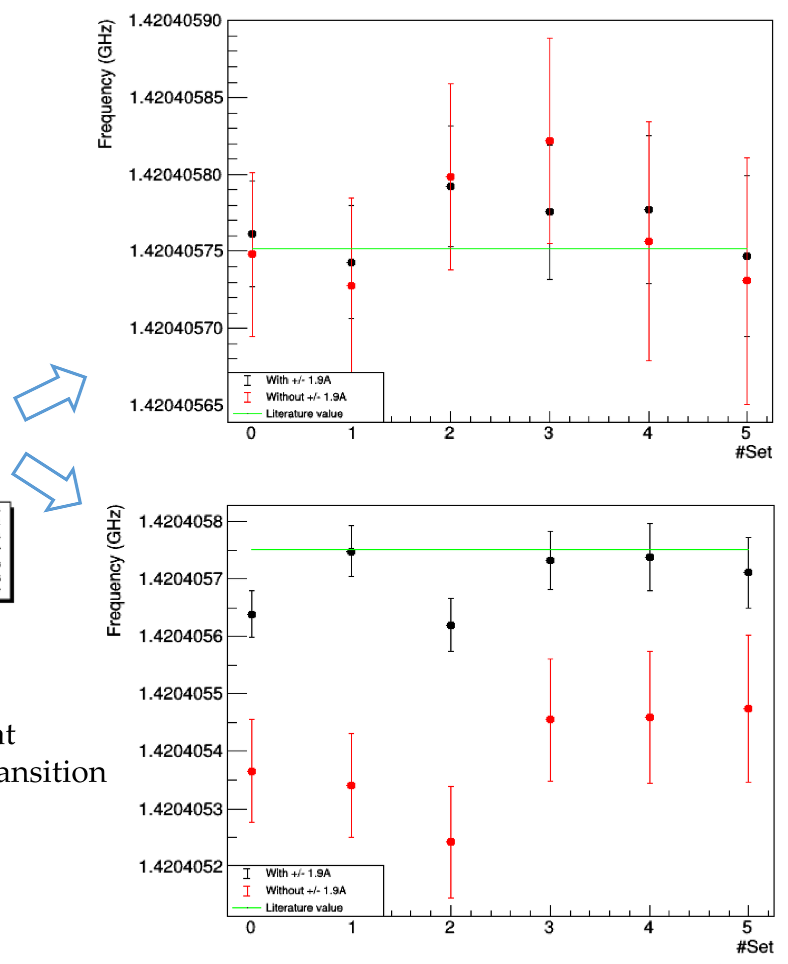
Resonance fit:
Resonance fit (red curve) done with a bivariate spline interpolation using data simulated by solving optical Bloch eq. for 2-level system.



Evaluation:
Extrapolating measured transition frequencies at several static B-fields (ν_σ, ν_π) to zero B-field transition frequency ν_0:

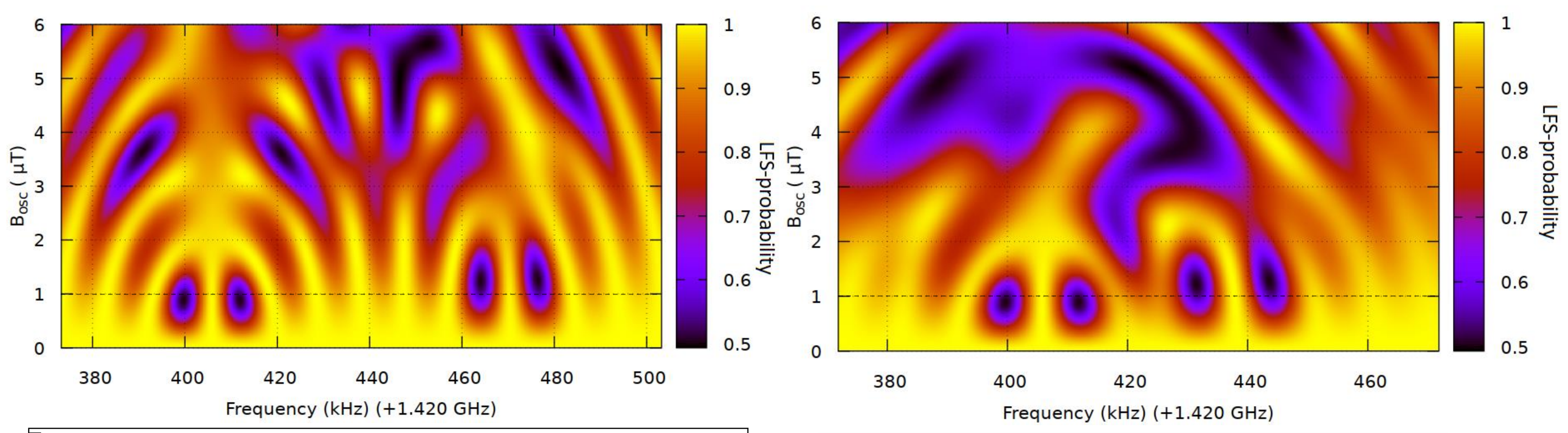
$$\nu_\sigma = \nu_0\sqrt{1+\left(\frac{(g_I-g_J)\mu_B B}{\nu_0 h}\right)^2}$$

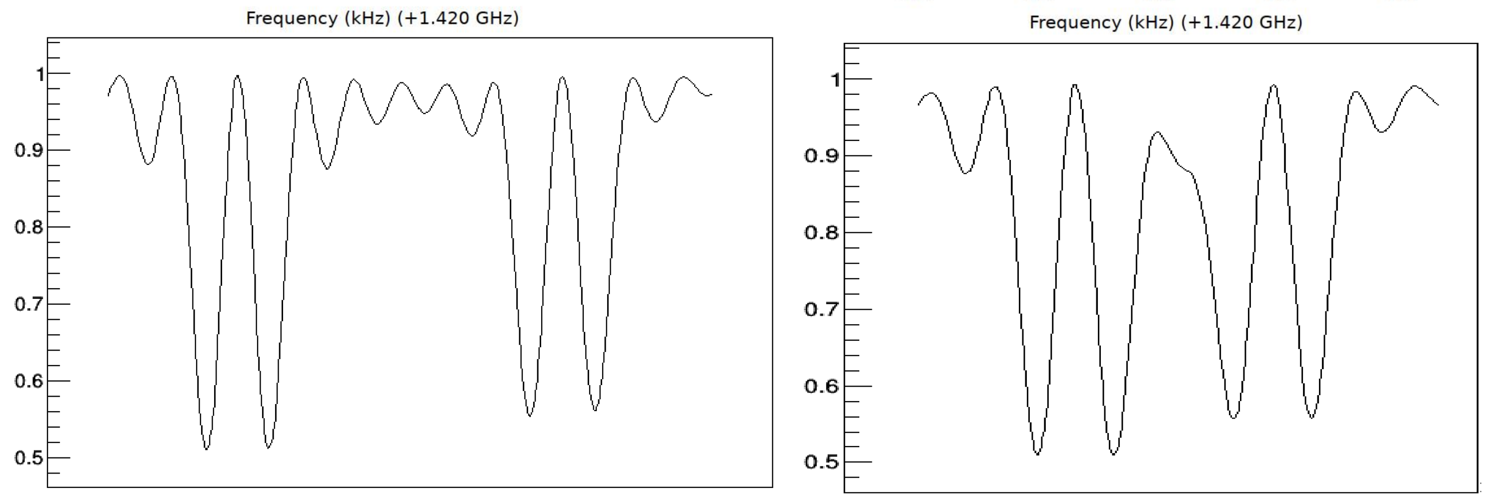
$$\nu_\pi = \frac{\nu_0}{2} + \frac{(g_J+g_I)\mu_B B}{2} + \frac{\nu_0}{2}\sqrt{1+\left(\frac{(g_I-g_J)\mu_B B}{\nu_0 h}\right)^2}$$



Result extrapolation to zero B-field:
Top: σ_1-transition data
Bottom: π_1-transition data

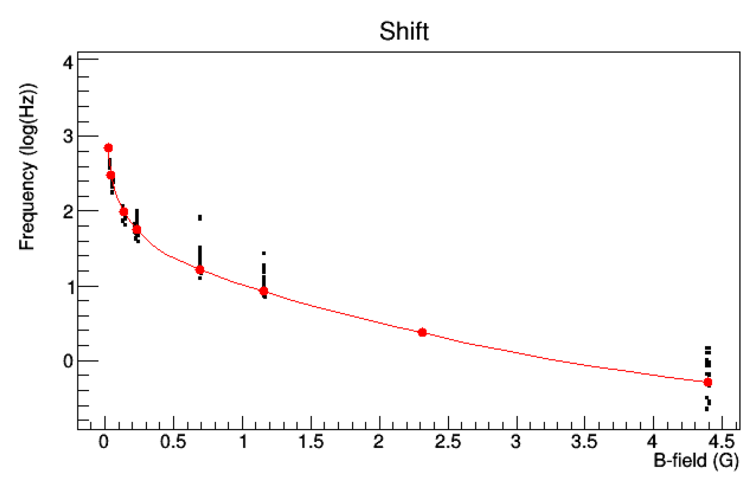
Transition probability calculated with 4-level system



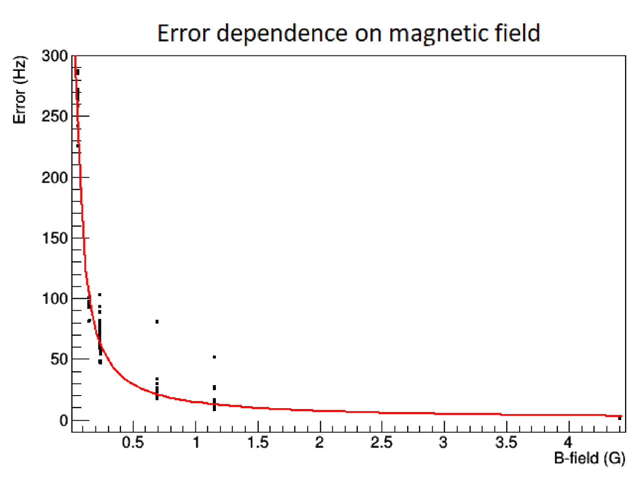


Top: Simulation of transition probability on the oscillating B-field amplitude and the frequency at a static B-field of 46 mG (left) and 23 mG (right). LFS-probability is the probability of measuring a LFS at the detector.
Bottom: Projection of the transition probability at an oscillating B-field of 1μT.

Results

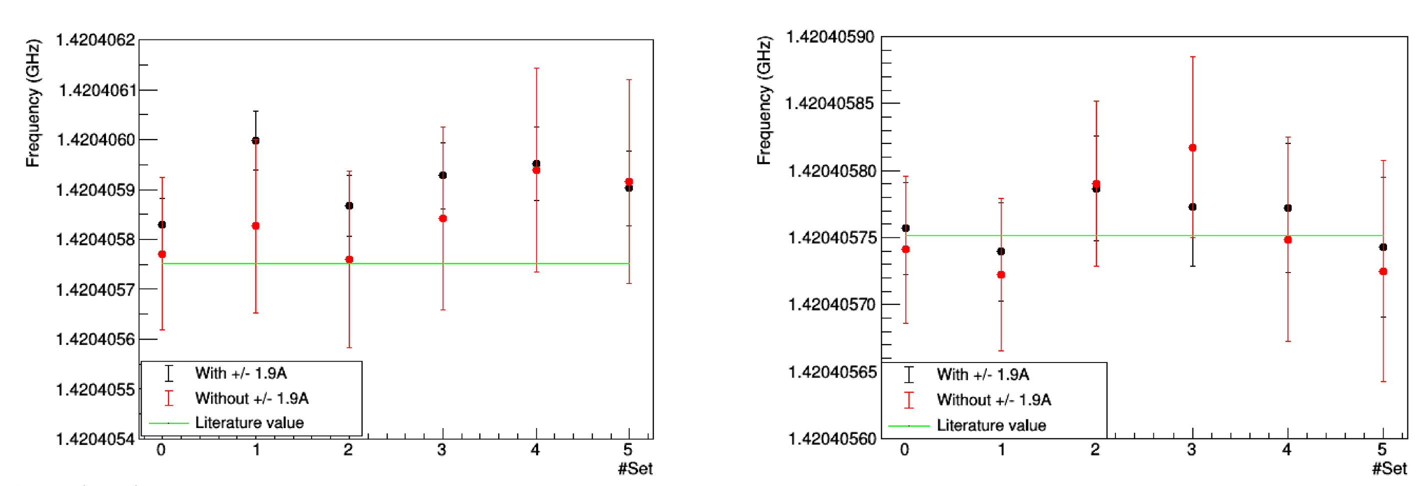


Shift of 2-level- vs. 4-level calculation:
The simplified evaluation using a 2-level-system shifts the transition frequency result at small static B-fields.



Error dependence on B-field:
The uncertainty of the hyperfine transition frequency using 4-level system increases with smaller static magnetic field due to increasing sensitivity on the oscillating B-field.

Correcting data



Applied correction:
Applying this shift as a correction on the π_1 – (left) and σ_1 – (right) – data. The GS-HFS results evaluated by the π_1 – transition shift towards the literature value, while the σ_1 – transition evaluation is hardly effected by this correction.

Summary & Outlook

- Spectroscopy apparatus works as expected and can be used for antihydrogen measurement.
- 45° angle between static and oscillating B-field to induce σ_1 – and π_1 – transition in the same cavity should be avoided because of the interference between the two transitions.
- Small static B-fields should be avoided.
- Additional B-field measurement should be performed to compensate possible residual fields.

References

[1] M. Diermaier. *Determination of the Hydrogen Ground-State Hyperfine Splitting in a Beam and Perspectives for Antihydrogen*. PhD thesis, Technical University of Vienna, 2016.
[2] A. Lanz. *Hydrogen Hyperfine Structure Measurements using the σ_1- and π_1- Transitions: Evaluation & Correction*. Master's thesis, University of Vienna, 2019.
[3] I. I. Rabi, S. Millman, P. Kusch and J. R. Zacharias. *The molecular beam resonance method for measuring nuclear magnetic moments. the magnetic moments of $_3Li^6$, $_3Li^7$ and $_9F^{19}$*. Phys. Rev., 55:526-535, Mar 1939

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† http://www.cern.ch/ASACUSA

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