Rabi Experiments on the σ and π Hyperfine Transitions in Hydrogen and Status of ASACUSA's Antihydrogen Program

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We report on the status of the in-beam hyperfine-structure measurements on ground-state antihydrogen by ASACUSA and on recent results obtained in supporting measurements from hydrogen. The σ_1 and π_1 transitions can now be investigated, which is beneficial from both theoretical and experimental perspectives. We discuss systematic effects from resonance interference originating from the chosen field geometries in the interaction region, and how their impact can be managed by appropriate data-taking or design concepts.

1. Status of ASACUSA's antihydrogen program

ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) is one of several collaborations studying antimatter at the antiproton decelerator at CERN. The majority of experiments in this area compare antimatter properties to those of their matter counterparts for a precise test of CPT symmetry. Recent results on the magnetic moment of the antiproton¹ by BASE as well as the $1S-2S$,² $1S-2P$,³ and hyperfine transitions⁴ of antihydrogen ($\bar{H}$) by ALPHA⁵ demonstrate the rapid progress in this field. All existing measurements confirm CPT symmetry within their respective uncertainties. Thus, the quest for ever higher precision tests by the antiproton-decelerator community continues. In this spirit, ASACUSA is working toward a hyperfine-splitting determination based on Rabi spectroscopy. The SME coefficients, which can be tested or constrained by this specific experiment have been discussed in the proceedings of the previous meeting in this series.⁶ The approach followed by ASACUSA requires the formation of a beam of $\bar{H}$ and offers the advantage that the actual measurement, i.e., the interaction with microwaves, takes place in a well-controlled

*http://asacusa.web.cern.ch/ASACUSA/asacusaweb/members_files/members.shtml

environment far away from the strong fields and field gradients of the trap for $\bar{\text{H}}$ formation.^{7,8} The observation of extracted antiatoms had been reported in Ref. 9, and later this beam had its quantum-state distribution characterized in Ref. 10. Ground-state $\bar{\text{H}}$ has clearly been observed. However, a rate increase is still needed before spectroscopic measurements with reasonable acquisition times can commence.

Due to the current long shutdown at CERN, antiproton physics is on hold until 2021. Then, the Extra-Low ENergy Antiproton ring (ELENA) will be in operation and the $\bar{\text{H}}$ experiment of ASACUSA will receive a dedicated beamline. Therefore, the multi-trap setup does not have to be removed from the zone anymore in order to make space for other antimatter studies pursued by ASACUSA. Currently, the setup is being installed at its final position and matter studies (i.e., mixing of protons and electrons) are planned to continue optimizing the formation process during the shutdown.

2. Transitions within the hyperfine sublevels

The two transitions that occur between a low-field seeking triplet state ($F=1$) and the singlet state ($F=0$) are called σ_1 and π_1 transitions (see Table 1). Those are accessible in a Rabi-type experiment and approach the value of interest at zero field. In the interaction volume, one has to provide both an oscillating magnetic field B_{osc} at 1.42 GHz to stimulate hyperfine transitions, and an external static magnetic field B_{ext} to control the Zeeman shift. A key difference between the two transitions is that they need different relative orientations of B_{osc} and B_{ext} . The component of B_{osc} aligned parallel to B_{ext} stimulates the σ_1 transition, and the orthogonal one the π_1 transition. In the ASACUSA setup, these fields are provided by a cavity of strip-line geometry with a large acceptance and surrounding coils.

Table 1. Properties of the hyperfine sublevels of ground-state $\bar{\text{H}}$.

state: $ F, M_F\rangle$	Zeeman shift	Stern–Gerlach	σ_1	π_1
$ 1, -1\rangle$	1 st O (linear)	low-field seeker		initial
$ 1, 0\rangle$	2 nd O (hyperbolic)	low-field seeker	initial	
$ 1, 1\rangle$	1 st O (linear)	high-field seeker		
$ 0, 0\rangle$	2 nd O (hyperbolic)	high-field seeker	final	final

In the low-field regime, the σ_1 transition has a weak magnetic-field sensitivity making it more robust against systematic effects. However, it is also insensitive to SME coefficients,¹¹ which relates to the fact that $\Delta M_F=0$.

Fig. 1. ASACUSA's devices for providing an oscillating B_{osc} and external static magnetic field B_{ext} in the interaction region of the Rabi experiment using microwave cavities and coil configurations.

In contrast, the π_1 transition probes the nonrelativistic spherical SME coefficients $g_{w(2q)10}^{\text{NR}(0B)}$, $g_{w(2q)10}^{\text{NR}(1B)}$ (CPT odd) and $H_{w(2q)10}^{\text{NR}(0B)}$, $H_{w(2q)10}^{\text{NR}(1B)}$ (CPT even).^{6,11} Control over systematic effects is a much stronger experimental challenge due to the first-order shift with B_{ext} of 14 Hz/nT.

Helmholtz coils produce a sufficiently homogeneous static field to investigate the σ_1 transition ($\sigma_{|B|}/|\bar{B}| < 5\%$). The cavity providing the oscillating field is placed within those coils in such a way that the required parallel alignment is achieved, as shown in the left panel of Fig. 1. For more details and a description of the entire H-beam setup for commissioning the hyperfine spectrometer, see Ref. 13. A determination of the H hyperfine structure with 2.7 ppm precision in agreement with the literature value was accomplished¹² by measuring the σ_1 transition at various static-field values and extrapolating to zero field. However, as mentioned before the σ_1 transition is not the first choice for a CPT test, which motivated upgrades of the interaction apparatus for investigations of the π_1 transition.

We designed McKeehan-like coils¹⁴ to provide a more homogeneous magnetic field ($\sigma_{|B|}/|\bar{B}| < 0.1\%$). The cavity can be rotated in steps of 45° within the coil arrangement thereby providing flexible alignment of B_{osc} to B_{ext} . A 45° alignment enables simultaneous access to both transitions. The upgraded device is shown in the right panel of Fig. 1.

3. Interference effect and future measurements and devices

At small B_{ext} , the separation of the σ_1 and π_1 transitions becomes comparable to the line widths, which is on the order of 10 kHz as the interaction time is typically $100 \mu\text{s}$ (beam velocity $\sim 1 \text{ km/s}$, cavity length $\sim 100 \text{ mm}$). For example, at $4.6 \mu\text{T}$ the separation decreases to 65 kHz, and the interference leads to asymmetric line shapes and systematic shifts of the extracted

central frequencies, if one applies the symmetric fit function for a two-level system in this regime. Currently, we apply corrections for the effect, and the development of a fit procedure based on the complete four-level system of the ground-state hyperfine states is under consideration. On the other hand, the interference effect and resulting systematic shifts can be avoided with purely parallel or orthogonal alignment of the fields. This clean solution will be realized in a Ramsey apparatus that is currently in its final design phase.¹⁶ In principle, the respective alignment can also be adjusted in steps of 45° with the present Rabi apparatus. However, a change requires breaking the vacuum. In this design, the advantageous opportunity for interleaved measurements of π_1 and σ_1 transitions is tied to the alignment of the fields that also gives rise to the interference effect. By operating at sufficiently high B_{ext} (e.g., $23/69/115\ \mu\text{T}$ as in Ref. 15) the systematic shifts and related uncertainties can easily be kept below ~ 10 ppb, an acceptable level for the anticipated first-stage results on $\bar{\text{H}}$. A measurement of a single pair of a π_1 and σ_1 transitions in this regime of B_{ext} provides a reliable way to determine the zero-field splitting from a calculation,¹⁵ i.e., without extrapolating to zero field by a fit. Thus, the present apparatus is well suited for a first Rabi-type SME-sensitive $\bar{\text{H}}$ hyperfine-structure measurement.

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