Progress towards the first measurement of the antihydrogen Lamb shift

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This work is supported by ETH Research Grant (ETH-46 17-1)
Introduction: Matter-antimatter asymmetry

- Standard Model (SM) predicts equal amount of matter and antimatter produced right after Big Bang

- Observations disagree with SM → new theories arose, e.g. Standard Model Extension (SME) [*]

- SME is built from SM and General Relativity and includes Lorentz- and CPT violating operators

- SME coefficients need to be determined experimentally

[*] Colladay, D., & Kostelecký, V. A.  
**Introduction: Tests of CPT**

**ALPHA (2016)**

**ALPHA (2017)**

**ASACUSA (ongoing)**
Measurement of the hyperfine structure of antihydrogen in a beam

**GBAR (presented in this talk)**
P. Crivelli, D. Cooke, M. Heiss, Antiproton charge radius

Adapted from: E. Widmann et al., Hyperfine Interact. 215, 1 (2013).
Introduction: Gross energy spectrum of 2-body atom

- The atomic gross structure of the atomic energy levels is given by the Bohr and the Schrödinger equation (SEQ) with the Coulomb potential:

\[ E_n = -\frac{(Z\alpha)^2 m_R c^2}{2n^2} \]

- The use of the reduced mass

\[ m_R = \frac{M m}{M + m} \]

- takes into account the finite mass of the nucleus providing a first (non-relativisitic) corrections
Introduction: Relativistic effects

Energy

- n=3
- n=2
- n=1

Bohr
- 1S\(_{1/2}\)

Dirac
- 2S\(_{1/2}\), 2P\(_{1/2}\)
- 2P\(_{3/2}\)

Relativistic effects

Bohr

Dirac

Zurich PhD Seminar 2018
Introduction: QED effects

Energy

n=3

n=2

2P_{3/2}

2S_{1/2}, 2P_{1/2}

2P_{1/2}

Relativistic effects

QED effects

n=1

Bohr

Dirac

Lamb
Introduction: Corrected energy spectrum of Hydrogen

- Energy levels for $n=1$, $n=2$, and $n=3$
- Bohr, Dirac, Lamb, HFS-splitting, finite-size effect
- Relativistic, QED, Nuclear structure effects

Energy levels:
- $n=1$:
  - $1S_{1/2}$
  - $F=0$, $F=1$
- $n=2$:
  - $2S_{1/2} \text{, } 2P_{1/2}$
  - $F=0$, $F=1$
  - $2P_{3/2}$
- $n=3$

Additional effects:
- Relativistic effects
- QED effects
- Nuclear structure effects
Introduction: Lamb’s experiment

- Basic idea: produce a beam of hydrogen atoms in the metastable 2S state, $\tau_{2S} = 10^8\text{ ns} = 100\text{ ms}$, by bombarding ground state atoms with electrons
  - The atoms in the 2S impinging on a metal surface release their electrons that can be detected with an electrometer while this process does not occur for the atoms in the ground state (1S)
Introduction: Lamb’s experiment

- Applying an RF field at the resonance frequency one can induce transition from the 2S to the 2P state
  - The 2P state, $\tau_{2p} \approx 1 \text{ ns}$, decays quickly to the ground state and therefore the signal in the electrometer will decrease
Introduction: Lamb shift measurement

- An additional contribution to the Lamb shift is given by the finite size of the (anti-)proton:
  \[
  \Delta E_{\text{nucl}} = \frac{2(Z\alpha)^4}{3} \frac{m_R}{n^3} m_R^2 R_p^2
  \]

- by measuring the Lamb shift of antihydrogen, one can determine the antiproton charge radius

- Goal: Measuring the antihydrogen Lamb shift at a precision of 100ppm, which allows to extract the antiproton charge radius at a level of 10%.
Experiment: $\bar{H}(2S)$ beam formation

- $\bar{p}$ from ELENA in AD hall at CERN
- Positrons from the intense slow positron beam from GBAR
- Charge exchange reaction: $\bar{p} + Ps \rightarrow \bar{H} + e^-$
- H formation with protons already been measured in good accordance with calculations [*]
- Cross section for $\bar{H}(2S)$ formation similar to $\bar{H}(1S)$ at an antiproton energy of 6 keV

Experiment: Proposed scheme

\[ v \sim 1 \text{ mm/ns} \]
\[ \tau(2S) \sim 100 \text{ ms} \]
Experiment: HFS selector

- Several 2S and 2P hyperfine levels
- In order to reduce distortion of the resonance line shape, $2S_{1/2}$ $F=0$ state is isolated
- Method: single frequency to drive down all the $2S_{1/2}$ $F=1$ to short lived $2P_{1/2}$, shown by Newton et al. [*]
  -> 1% of $F=1$, but 60% of $F=0$ retained

[*] G. Newton, D.A. Andrews, P.J. Unsworth
Experiment: Single Ly-α detector

Micromegas:

- Prototype with MgF₂ window and Ar/DME filling gas (90/10) built and tested

- Differentiation between cosmosics / antiprotons and Ly-α possible

- Low efficiency due to
  - small photoionization yield at 121nm (~15%)  
  - loss through window (~50%)  
  - difficulty to distinguish signal from noise  
→ improvable with other gas mixtures
Experiment: Single Ly-α detector

Microchannel Plate (MCP):

- Two plates for higher gain (~10^7)
- Deposition of CsI on top plate as converter (~50% quantum efficiency) [*]
- Estimated detection efficiency for single Ly-α ~40%
- Tests with a 1 inch MCP confirmed this estimated detection efficiency
- Difficult to handle: CsI highly hygroscopic, assembly needs to be done in nitrogen atmosphere

Single Ly-α detector

- Tests done with a self-made Ly-α source based on the principle of a low pressure discharge lamp
- Source with Ly-α filter and possibility to tune flux
- Calibrated with a solar blind PMT with known efficiency
- Measured rates up to 400 MHz
Single Ly-α detector

Two ring electrodes on opposite voltages

Copper plate to shield from microwave

Grounded tungsten grid, 92% transparency, for shielding MCP from stray fields

MCP structure, active area 50.8 x 50.8 mm²

SIMION simulation: 41.5% solid angle covered
Current Status & Outlook

- Lamb shift measurement of $\bar{H}$ at a level of 100ppm seems possible with roughly one month of data taking, thanks to ELENA and GBAR LINAC. The accuracy is limited by statistics (~ 1000 detected events per day, possible improvements).
- 1 inch circular MCP prototype successfully tested
- Most of Ly-α detector parts either ordered or in production, assembly is foreseen in April 2018
- First goal: detection of production of H(2S) via charge exchange (May-July 2018)
- First attempts with $\bar{H}$ can already be done before LS2 assuming ELENA and Ps production working like scheduled (Sept. – Nov. 2018)