MEASUREMENT OF THE HYDROGEN HYPERFINE SPLITTING:
TOWARDS ANTIHYDROGEN SPECTROSCOPY

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MOTIVATIONS

10 000 000 001
MATTER

10 000 000 000
ANTIMATTER

SEPT 11TH 2017
— EXA 2017 — VIENNA —
CHLOÉ MALBRUNOT
MOTIVATIONS

10 000 000 001
MATTER

10 000 000 000
ANTIMATTER
MOTIVATIONS

10 000 000 001
MATTER

10 000 000 000
ANTIMATTER

PRECISION

NEUTRALITY
MOTIVATIONS

CPT Theorem
Quantum Field Theory
Lorentz invariance
Locality
Unitarity
MOTIVATIONS

CPT Theorem
Quantum Field Theory
Lorentz invariance
Locality
Unitarity

Implies: properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment)
MOTIVATIONS

CPT Theorem
Quantum Field Theory
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Implies: properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment)

Atomic structures identical
MOTIVATIONS

CPT Theorem
Quantum Field Theory
Lorentz invariance
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Unitarity

Implies: properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment)

Atomic structures identical

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HYDROGEN

1

Bohr  Dirac  Lamb  HFS

F=1
F=0
```
Tests in different systems:

- Positron $g$
- Muon $g$
- Antiproton $q/m$
- Antiproton $g$
- Antihelium $m/q$
- Antideuteron $m/q$

Relative precision:

- $\bar{H} \frac{1S}{2S}$
- $\bar{H}$ GS HFS

Planned
Recent
Past
MOTIVATIONS

\[ \nu = 1.420405751768(1) \text{ GHz} \]


Leading term: Fermi contact term

\[ \nu_F = \frac{16}{3} \left( \frac{M_p}{M_p + m_e} \right)^3 \frac{m_e \overline{\mu_p}}{M_p \mu_N} \alpha^2 c R_y \]

has been measured to better than 1 ppm


Finite electric and magnetic radius (Zemach corrections): ∼41 ppm

access to the electric and magnetic form factors of the antiproton

\[ \Delta \nu (\text{Zemach}) = \nu_F \frac{2Z \alpha m_e}{\pi^2} \int \frac{d^3p}{p^4} \left[ \frac{G_E(p^2) G_M(p^2)}{1 + \kappa} \right] - 1 \]

Polarizability of \( p(\bar{\text{b}}) = 1.88 \pm 0.64 \) ppm

Carlson, Nazaryan, and Griffioen PRA 78, 022517 (2008)

Remaining deviation theory-experiment: 0.86±0.78 ppm


MOTIVATIONS

Standard model extension (SME)


Dirac equation in mSME:

\[
(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0
\]

Different measurements (even of the same quantity) are sensitive (or not) to different SME coefficients
MOTIVATIONS

Measure $\nu_{HF}$ in antihydrogen:

- $\pi_1 - \pi_2$
- $\pi_1 & \sigma_1$

at a given field

Measure $\pi_1 - \pi_2$ at a given field

$\nu_0 = \frac{g_+ \sqrt{g_+^2 \nu_o - 4g_+^2 \nu_o^2 + 4g_+^2 \nu_o + g_+^2 (2\nu_o - \nu_o)}}{g_+^2 + g_-^2}$

where $g_\pm = g_I \pm g_J$. 
MOTIVATIONS

Measure $\nu_{HF}$ in antihydrogen:

\[
\begin{align*}
\pi_1 - \pi_2 \\
\pi_1 & \& \sigma_1
\end{align*}
\]

at a given field

Extrapolate either transition from several measurements at different fields

\[
\nu_0 = \frac{g_1 \sqrt{g_2^b \nu_2^b - 4g_2^b \nu_2^b + 4g_2^b \nu_2^0 + g_2^b(2\nu_2 - \nu_0)}}{g_2^b + g_2^b}
\]

where $g_\pm = g_1 \pm g_2$.
MOTIVATIONS

Measure $\nu_{HF}$ in antihydrogen:

- $\pi_1 - \pi_2$
- $\pi_1$ & $\sigma_1$

Extrapolate either transition from several measurements at different fields

All are CPT tests

But not all constrain SME parameters

\[ \nu = \frac{g_1 \sqrt{g_0^2 \nu_0^2 - 4g_0^2 \nu_0^2 + 4g_0^2 \nu_0 + g_0^2 (2\nu_0 - \nu_0)}}{g_0^2 + g_0^2} \]

where $g_\pm = g_1 \pm g_3$. 
MOTIVATIONS

Measure $\nu_{HF}$ in antihydrogen:

- $\pi_1 - \pi_2$
- $\pi_1 \& \sigma_1$

Extrapolate either transition from several measurements at different fields.

Measurements motivated in the framework of SME for both hydrogen and antihydrogen.

But not all constrain SME parameters.

\[ \nu_0 = \frac{g_1 \sqrt{g_1^2 \nu_e^2 - 4g_1^2 \nu_\pi^2 + 4g_2^2 \nu_\pi \nu_\sigma + g_2^2(2\nu_\sigma - \nu_e)}}{g_1^2 + g_2^2} \]

where $g_\pm = g_1 \pm g_2$.

All are CPT tests.

$1^2S_{1/2}$

$F = 1$

$F = 0$

$\text{B (T)}$

$|d\rangle$

$|\uparrow\uparrow\rangle$

$|\downarrow\downarrow\rangle$

$|c\rangle$

$|\uparrow\downarrow\rangle$

$|\downarrow\uparrow\rangle$

$|b\rangle$

$|\downarrow\uparrow\rangle$

$|\uparrow\downarrow\rangle$

$|a\rangle$
HYDROGEN & ANTIHYDROGEN EXPERIMENTS @ CERN
**BEAM VS. TRAP**

**Advantage of beam:**
Absence of strong field gradient
Lower requirement on the temperature of antihydrogen atoms

**Inconvenient of beam:**
Need “focussing” (loss of solid angle)
Cannot easily control the quantum state at the detector
More difficult to control the polarization

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**ALPHA**

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**ASACUSA**
1ST HYDROGEN SETUP

Antihydrogen spectroscopy apparatus

@ CERN B165
1ST HYDROGEN SETUP

Hyperfine splitting (GHz)

External magnetic field (T)

Low field seekers

High field seekers

Antihydrogen spectroscopy apparatus
1ST HYDROGEN SETUP

“strip-line” cavity design
"strip-line" cavity design
Robust lineshape fit
Extraction of amplitude of oscillatory field, velocity and velocity spread

Spectroscopy apparatus if fully commissioned

\[ \nu_{HF} = 1420.405 \pm 748.4(3.4)(1.6) \, \text{Hz} \]

\[ \Delta \nu / \nu = 2.7 \, \text{ppb} \]

**Table 2 | Error budget.**

<table>
<thead>
<tr>
<th>Contribution</th>
<th>1σ s.d. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic error</td>
<td>1.62</td>
</tr>
<tr>
<td>Frequency standard</td>
<td></td>
</tr>
<tr>
<td>Common fit parameters</td>
<td>0.05</td>
</tr>
<tr>
<td>( \nu_H )</td>
<td>0.03</td>
</tr>
<tr>
<td>( \sigma_N )</td>
<td>0.02</td>
</tr>
<tr>
<td>Systematic error total (( \sigma_{sys} ))</td>
<td>1.62</td>
</tr>
<tr>
<td>Statistical error (( \sigma_{stat} ))</td>
<td>3.43</td>
</tr>
<tr>
<td>Total error (( \sigma_{tot} ))</td>
<td>3.79</td>
</tr>
</tbody>
</table>

In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

σ MEASUREMENT

ppm result with antihydrogen should be in reach if enough statistics can be gathered

error bar of a data point

\[ \delta \nu_c = \frac{C}{\varepsilon T_{int} \sqrt{N \Delta R}} \]

line-shape dependent factor

Interaction time

Number of data points

Count rate drop

Assuming background:
- 50% atoms are in excited states
- 50% of remaining are in wrong lfs state
- polarisation P=1/3

Assuming MB distribution @ 50K

For ppm measurement using 4 resonances we estimate ~ 8000 atoms should be recorded at the antihydrogen detector

\[ \mathcal{P} = \frac{f_{\text{LFS}} - f_{\text{HFS}}}{f_{\text{LFS}} + f_{\text{HFS}}} \]
Other possibility:

Measure $\pi_1$ & $\sigma_1$ at the same field (2 resonances needed, not sensitive to stray field (from the earth or from CUSP in the antihydrogen experiment)

Advantage: $\pi_1$ is sensitive to SME coefficients

BUT $\pi_1$ more sensitive to magnetic field inhomogeneities
Other possibility:

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BUT $\pi_1$ more sensitive to magnetic field inhomogeneities

\[ \delta f \propto \frac{\nu H}{L_{cav}} \approx \frac{1\text{ km/s}}{0.1\text{ m}} \approx 10\text{ kHz} \]
New Helmholz coils with corrections coils

Cavity tilted at 45° to allow both transitions at the same time

Rotation and up/down movements possible for systematic studies
MEASUREMENT

New Helmohlz coils with corrections coils

Cavity tilted at 45° to allow both transitions at the same time

Rotation and up/down movements possible for systematic studies

New 3-layers cylindrical shielding
First $\pi_1$ resonance observed
\( \pi \) MEASUREMENT

First \( \pi_1 \) resonance observed

\( \pi_1 \) & \( \sigma_1 \) measured at the same time and same field

ppb measurement in reach

Systematic studies for antihydrogen experiment
2ND HYDROGEN SETUP

Siderial variations constrained by Harvard-Smithsonian maser at mHz level

72 SME coefficients involved. 48 constrained, 24 remaining and can be constrained using different orientation of the static B-field

PHYSICAL REVIEW A 68, 063807 (2003)

Testing CPT and Lorentz symmetry with hydrogen masers

Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
(Received 4 August 2003; published 9 December 2003)
ANTIHYDROGEN SETUP

@ CERN B193

$\bar{p}$ TRAP $B=2.5T$

CUSP TRAP $B=2.7T$

FI chamber $E<20$ Knee/cm

MW Cavity

Analyzing $\bar{H}$ $B=3.5T$

$\bar{H}$ detector

e+ TRAP $B=0.3T$

e+ source $1.85 \times 10^9/s$
See talk by N. Kuroda at 3pm
ANTIHYDROGEN SETUP

@ CERN B193

See talk by N. Kuroda at 3pm

See talk of B. Kolbinger in P1 on Tuesday

\( \bar{p} \) TRAP
B=2.5T

CUSP TRAP
B=2.7T

FI chamber
\( E \leq 20 \text{ KV/cm} \)

MW Cavity

Analyzing \( \tilde{H} \)
B=3.5T

\( \tilde{H} \) detector

\( e^+ \) TRAP
B=0.3T

e+ source
1.85\( \times 10^9 \)/s
CONCLUSIONS

Two fronts:

- Hydrogen beam: ppb measurement achieved on $\sigma$ transition.

- Characterization of $\bar{H}$ beam $\rightarrow$ towards spectroscopy

New program with Hydrogen:

- Measurement of $\sigma$ and $\pi$

- Constraints on SME coefficients