Precision Spectroscopy of Antihydrogen in ALPHA

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The 1S-2S transition frequency in hydrogen is one of the most precisely measured numbers in physics:

\[ f_{1S - 2S} = 2\ 466\ 061\ 413\ 187\ 035\ (10)\ \text{Hz} \]

Comparing this value with its equivalent in antihydrogen is one of the most appealing and conceptually simple matter / antimatter comparisons, and is one of the main motivations for doing cold antimatter physics.
The ALPHA Experiment

a. Diagram showing the experimental setup with various components such as solenoids, electrodes, mirror coils, octupole, and a cavity output coupler.

b. Graph showing the field strength (T) vs. axial position (mm) with peaks at various field strengths and axial positions.

1. Antiproton preparation
2. Positron preparation
3. Antihydrogen synthesis and trapping
4. Cavity input coupler
5. Piezo stack
6. Annihilation detector

C. Ø. Rasmussen
Hydrogen 1S and 2S Hyperfine Structure

E - E_{1S-2S} (GHz)

\begin{align*}
|2S_a\rangle \\
|2S_b\rangle \\
|2S_c\rangle \\
|2S_d\rangle \\
|1S_a\rangle \\
|1S_b\rangle \\
|1S_c\rangle \\
|1S_d\rangle
\end{align*}

B-field (T)

Trappable states

Non-trappable states

f_{d-d}

f_{c-c}

Experimental Procedure

- Trap antihydrogen from two mixing cycles (about 20 atoms)
- Clear out any remaining charged particles
- 300s hold time at d-d frequency
- 300s hold time at c-c frequency
- Ramp down magnets to detect remaining atoms

3 types of trials:
- On resonance
- Off resonance
- No laser

11 repetitions of each type were conducted
Simulation

Simulate the response of ordinary hydrogen in the ALPHA trap
Data: Disappearance mode

Count the atoms left in the trap after the laser exposure. On- and off- resonance differ by $92 \pm 15$ counts

<table>
<thead>
<tr>
<th>Type</th>
<th>Detected events</th>
<th>Background</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-resonance</td>
<td>159</td>
<td>0.7</td>
<td>13</td>
</tr>
<tr>
<td>On-resonance</td>
<td>67</td>
<td>0.7</td>
<td>8.2</td>
</tr>
<tr>
<td>No laser</td>
<td>142</td>
<td>0.7</td>
<td>12</td>
</tr>
</tbody>
</table>

Detector efficiency here is 0.688
## Data: Appearance mode

Look for annihilations during the 300s hold times

<table>
<thead>
<tr>
<th>Type</th>
<th>Detected events</th>
<th>Background</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>d-d off resonance</td>
<td>15</td>
<td>14.2</td>
<td>3.9</td>
</tr>
<tr>
<td>d-d on resonance</td>
<td>39</td>
<td>14.2</td>
<td>6.2</td>
</tr>
<tr>
<td>No laser</td>
<td>22</td>
<td>14.2</td>
<td>4.7</td>
</tr>
<tr>
<td>c-c off resonance</td>
<td>12</td>
<td>14.2</td>
<td>3.5</td>
</tr>
<tr>
<td>c-c on resonance</td>
<td>40</td>
<td>14.2</td>
<td>6.3</td>
</tr>
<tr>
<td>No laser</td>
<td>8</td>
<td>14.2</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>total off resonance</strong></td>
<td><strong>27</strong></td>
<td><strong>28.4</strong></td>
<td><strong>5.2</strong></td>
</tr>
<tr>
<td><strong>total on resonance</strong></td>
<td><strong>79</strong></td>
<td><strong>28.4</strong></td>
<td><strong>8.9</strong></td>
</tr>
<tr>
<td><strong>total No laser</strong></td>
<td><strong>30</strong></td>
<td><strong>28.4</strong></td>
<td><strong>5.5</strong></td>
</tr>
</tbody>
</table>

Detector efficiency here is 0.376
2016 Result

Normalized signal

Detuning, D (kHz @ 243 nm)

Disappearance 2016
Appearance 2016
1000 mW Simulation

C. Ø. Rasmussen
Drive only the d-d transition

- Trappable states
- Non-trappable states

Energy - $E_{1S-2S}$ (GHz)

Magnetic field (T)

$|1S_d\rangle$

$|1S_b\rangle$

$|2S_d\rangle$

$|2S_b\rangle$

$|1S_a\rangle$

$|2S_d\rangle$

$|2S_b\rangle$

Energy (GHz)

Magnetic field (T)

$f_{d-d}$

(laser)

$f_{c-b}$

($\mu$-wave)
Experimental Procedure

- Trap antihydrogen from three mixing cycles (about 40 atoms)
- Clear out any remaining charged particles
- 300s laser exposure at fixed frequency near d-d transition
- 32s microwave sweep to eject c-state atoms
- Ramp down magnets to detect remaining atoms

- Interspersed trials of 4 different laser frequencies in a frequency ‘set’
- 4 sets of 4 frequencies completed over 10 weeks
- 0 kHz and -200 kHz detuning included in every set
- +25 kHz repeated as another check of reproducibility
- 9 unique laser frequencies used on ~ 15,000 atoms
- 21 repetitions of type of trial
2017 Result

Normalized signal vs. Detuning, D (kHz @ 243 nm)

- Disappearance, $r_s(D)$
- Appearance, $r_l(D)$

1000 mW Simulation
Effect of Laser Power

![Graph showing the effect of laser power on signal normalized to 1000 mW, with curves for 1150 mW Simulation, 1000 mW Simulation, and 900 mW Simulation, and an inset showing FWHM as a function of laser power.](image)
Result

- The line shape is in good agreement with the hydrogen calculation.
- The center frequency is determined to a fractional precision of about $2 \times 10^{-12}$ and is in agreement with the hydrogen calculation.
- This is currently the best "antimatter clock"
Understanding the Line Width

Shifts and broadening effects calculated assuming 1W of circulating laser power and typical trap parameters

<table>
<thead>
<tr>
<th>Effect</th>
<th>Approximate Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st order Doppler</td>
<td>cancels</td>
</tr>
<tr>
<td>2nd order Doppler</td>
<td>80 Hz</td>
</tr>
<tr>
<td>Transition time</td>
<td>160 kHz</td>
</tr>
<tr>
<td>AC Stark</td>
<td>5 kHz</td>
</tr>
<tr>
<td>DC Stark</td>
<td>150 Hz</td>
</tr>
<tr>
<td>Magnetic shift d-d (c-c)</td>
<td>96 Hz/G (1.9 kHz/G)</td>
</tr>
<tr>
<td>Ionisation width</td>
<td>4 kHz</td>
</tr>
</tbody>
</table>
Reducing the Line Width

The main contribution to the line width is the transit time broadening.

Thus, substantial narrowing can be achieved through:

- Increasing the laser beam size (realistically a factor 2)
- Adiabatic cooling of the $\bar{\text{H}}$ (Maybe a factor 2?)
- Laser cooling! (large improvement possible)
1S-2P Spectroscopy

- Accumulate antihydrogen from $\sim$ 30 mixing cycles (about 500 atoms in two hours)
- Illuminate with 12 different laser frequencies, repeatedly and in randomized order
- Look for annihilations in a short window around the laser pulse
- Repeat the whole sequence four times
1S-2P Spectroscopy

Agrees with ordinary hydrogen to within $5 \times 10^{-8}$

Opens the door to laser cooling!
Competing with the Hydrogen 1S-2S measurement

We are still 3 orders of magnitude less precise than the Hydrogen measurement.

Short term gains can come from:
- Reducing the line width
- More statistics

Then, measure the systematics directly:
- Measure at several magnetic fields
- Measure at several laser powers (extract AC stark shift)
- Measure at several temperatures (extract or suppress 2nd order Doppler shift + DC stark shift)

These all require effort but are in no way impossible!
Ground state hyperfine splitting given by the separation of two spectral lines, driven at the same magnetic field.

\[ \Delta \nu = 1420.4 \pm 0.5 \text{ MHz} \]

\[ \]
CPT Tests and relative precision

- Relative precision
- prospective
- recent
- past

- \( ^3\text{He} \ q/m \)
- deuteron \( q/m \)
- \( K_0 \ \Delta m \)
- muon \( g \)
- \( e^+ \ g \)
- \( \bar{p} \ g \)
- \( \bar{p} \ q/m \)
- \( \bar{H} \ 1S-2S \)
- \( \bar{H} \ GSHF \)

Relative precision values:
- \( 10^{-21} \)
- \( 10^{-18} \)
- \( 10^{-15} \)
- \( 10^{-12} \)
- \( 10^{-9} \)
- \( 10^{-6} \)
- \( 10^{-3} \)
- \( 10^0 \)
CPT Tests on an Energy Scale

Comparing the sensitivity to absolute energy differences of various CPT tests

\[ m_p = m_{\bar{p}} \]

\[ m_{e^-} = m_{e^+} \]

\[ m_{K^0} = m_{\bar{K}^0} \]

\[ f_{H}^{1S-2S} = f_{H}^{1S-2S} \]

\[ f_{H}^{GSHF} = f_{H}^{GSHF} \]

\[ (q/m)_p = (q/m)_{\bar{p}} \]
# Table of uncertainties

<table>
<thead>
<tr>
<th>Type of uncertainty</th>
<th>Estimated size (kHz)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainties</td>
<td>3.8</td>
<td>Poisson errors and curve fitting to measured data</td>
</tr>
<tr>
<td>Modelling uncertainties</td>
<td>3</td>
<td>Fitting of simulated data to piecewise-analytic function</td>
</tr>
<tr>
<td>Modelling uncertainties</td>
<td>1</td>
<td>Waist size of the laser, antihydrogen dynamics</td>
</tr>
<tr>
<td>Magnetic-field stability</td>
<td>0.03</td>
<td>From microwave removal of $1S_c$-state atoms (see text)</td>
</tr>
<tr>
<td>Absolute magnetic-field measurement</td>
<td>0.6</td>
<td>From electron cyclotron resonance</td>
</tr>
<tr>
<td>Laser-frequency stability</td>
<td>2</td>
<td>Limited by GPS clock</td>
</tr>
<tr>
<td>d.c. Stark shift</td>
<td>0.15</td>
<td>Not included in simulation</td>
</tr>
<tr>
<td>Second-order Doppler shift</td>
<td>0.08</td>
<td>Not included in simulation</td>
</tr>
<tr>
<td>Discrete frequency choice of measured points</td>
<td>0.36</td>
<td>Determined from fitting sets of pseudo-data</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.4</strong></td>
<td></td>
</tr>
</tbody>
</table>
Laser System

- 150mW from laser
- 1W circulating in cavity
1S-2S Transition in Hydrogen

- $f_{1S-2S} = 2 466 061 413 187 035 (10) \text{ Hz}$
- Measured with a cold hydrogen beam

Hänsch et al. 2011
Future Improvements

Expansion of laser beam size:

- $w_0 = 100\,\mu\text{m}$
- $w_0 = 200\,\mu\text{m}$
- $w_0 = 300\,\mu\text{m}$
- $w_0 = 400\,\mu\text{m}$

Ionisation + Spin-flip

Detuning at 243nm (kHz)

FWHM (kHz)