Precision Spectroscopy of Antihydrogen in ALPHA

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1S-2S Spectroscopy

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

\[ f_{1S - 2S} = 2.466 \times 10^9 \text{ Hz} \]

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

1. Antiproton preparation
2. Positron preparation
3. Antihydrogen synthesis and trapping
4. Vacuum
5. Liquid helium
6. Air
7. Solenoid
8. Mirror coils
9. Octupole
10. Solenoid
11. Cavity output coupler
12. Axial Position (mm)
13. Field Strength (T)

C. Ø. Rasmussen

1S-2S Antihydrogen

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Laser System

- 150mW from laser
- 1W circulating in cavity
Hydrogen 1S and 2S Hyperfine Structure

- Trappable states
- Non-trappable states

$|2S_d\rangle$, $|2S_c\rangle$, $|2S_b\rangle$, $|2S_a\rangle$

$|1S_d\rangle$, $|1S_c\rangle$, $|1S_b\rangle$, $|1S_a\rangle$

$f_{d-d}$, $f_{c-c}$
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
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>total off resonance</td>
<td>27</td>
<td>28.4</td>
<td>5.2</td>
</tr>
<tr>
<td>total on resonance</td>
<td>79</td>
<td>28.4</td>
<td>8.9</td>
</tr>
<tr>
<td>total No laser</td>
<td>30</td>
<td>28.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Detector efficiency here is 0.376
Drive only the d-d transition
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
Effect of Laser Power

![Graph showing the effect of laser power on FWHM and Detuning, D (kHz @ 243 nm). The graph includes lines for different laser powers: 1150 mW Simulation, 1000 mW Simulation, and 900 mW Simulation. The inset graph shows a comparison of experimental data with simulations.](image-url)
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 Shape

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>
Future Improvements

The main contributions to the line width are:

- Transit time broadening
- Depletion effects

Reduction of linewidth to be gained through:

- Increasing the laser beam size
- Cooling the $\bar{\text{H}}$ (Laser cooling or adiabatic expansion)
- Operating at low depletion
Future Improvements

Expansion of laser beam size:

- $w_0 = 100\text{um}$
- $w_0 = 200\text{um}$
- $w_0 = 300\text{um}$
- $w_0 = 400\text{um}$

Graph showing the relationship between FWHM (kHz) and Detuning at 243nm (kHz) for different beam sizes.
Future Improvements

New measurement strategies:

- Measure at low magnetic field
- Measure at several laser powers (extract AC stark shift)
- Measure at several temperatures (extract 2nd order Doppler)

None of these are unthinkable!
Thank you
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
CPT Tests and relative precision

![Graph showing relative precision for various measurements](image)
CPT Tests on an Energy Scale

Comparing the sensitivity to absolute energy differences of various CPT tests

\[ m_p = m_{\bar{p}} \]
\[ m_e^- = m_{e^+} \]
\[ m_{K^0} = m_{\bar{K}^0} \]
\[ f_{1S-2S}^{H} = f_{1S-2S}^{\bar{H}} \]
\[ f_{H}^{GSHF} = f_{H}^{GSHF} \]
\[ \frac{q}{m_p} = \frac{q}{m_{\bar{p}}} \]
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>Total</td>
<td>5.4</td>
<td></td>
</tr>
</tbody>
</table>