Determining $\alpha$ from Helium Fine Structure

How to Measure Helium Energy Levels *REALLY* Well

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Outline

• Determining $\alpha$ from fine structure
  – why helium?
• Current Status of He fine structure
• Experimental Approach
  – improvements
• Brief Survey of Systematics
• Outlook and Conclusions
  – how well can we measure the intervals?
  – how accurately could we determine $\alpha$?
α from Fine Structure: Why Helium?

- Small ratio of linewidth to splitting

\[ \sigma \sim \frac{\Delta f}{f} = \frac{1.6 \text{ MHz}}{29616 \text{ MHz}} = 2.1 \cdot 10^{-5} \]

200 times better than Hydrogen!
Determining $\alpha$

$\nu_{01} = \alpha^2 \cdot 556 \, 200 \, 289.5 \, \text{MHz} + \Delta \nu_{\text{QED}}(\alpha^3, \alpha^4, \alpha^5, \ldots)$

- Larger interval used
- Assumes QED is correct

Testing QED

$\nu_{12} = \alpha^2 \cdot 43 \, 148 \, 532.9 \, \text{MHz} + \Delta \nu_{\text{QED}}(\alpha^3, \alpha^4, \alpha^5, \ldots)$

- Theoretical prediction for smaller interval

- G.W.F. Drake, CJP 80, 1195 (2002).
Present Status of Helium Fine Structure

Experimental agreement < 1 kHz

Two theoretical values disagree!

Significant disagreement between theory and experiment!
Experimental Values of $\alpha$

- Helium Spectroscopy: (12 ppb; -7$\sigma$)
- Helium Spectroscopy: (12 ppb; -12$\sigma$)
- Muonium Hyperfine Structure: (58 ppb; +0.3$\sigma$)
- Protron g': (31 ppb; -2.7$\sigma$)
- Neutron de Broglie $\lambda$: (34 ppb; +0.5$\sigma$)
- Quantum Hall Effect: (18 ppb; +0.8$\sigma$)
- Cs h/m: (8.0 ppb; +0.8$\sigma$)
- Rb h/m: (6.7 ppb; -0.4$\sigma$)
- UW electron g-2: (3.8 ppb; -0.6$\sigma$)
- 2002 CODATA: (3.3 ppb)
- Harvard electron g-2: (0.7 ppb; +1.3$\sigma$)
- 2002 CODATA: (3.3 ppb)

Warning! Theory and Expt Disagree!

700 Hz error in $\nu_{01}$ → 12 ppb in $\alpha$

Can we do better?
Objectives

• Goals
  – improve measurements the $2^3P$ fine structure splitting
  – measure the $2^3S$-$2^3P$ optical transition frequencies

• Test QED

• Determine $\alpha$

• Study properties of helium

• Develop techniques for laser spectroscopy
Experimental Setup

- Doppler-free saturated absorption spectroscopy
- External cavity diode laser at 1083 nm
- Scan laser offset-locked from a second stabilized diode laser
- Vertical magnetic field resolves sublevels
Frequency Reference Stability

- Frequency-doubled Nd:YAG NPRO
- Hyperfine transitions in $^{127}\text{I}_2$ at 532 nm
- Modulation Transfer Spectroscopy (MTS)
Optical Frequency Combs

\[ f_n = n f_{\text{rep}} + \delta \]

- Thousands of optical frequencies
- RF/microwave spacing
- RF/microwave offset
- Integer \( \sim 10^5 \)

- KEY IDEA: Thousands of optical frequency \( f_n \) are determined by two microwave frequencies
- Comb can extend over IR and visible regions - thousands of teeth!

\[ l(n) \]
Using the Optical Frequency Comb

- Transfers stability of iodine reference to 1083 nm
- Narrow 2 kHz NPRO linewidth transferred to all wavelengths
- Counting $f_{\text{rep}}$ accurately determines optical transition frequency

Experimental Lineshapes

\(2^3S-2^3P_0\)
- m=0 transition
- 7 parameters

\(2^3S-2^3P_1\)
- m=±1 transitions
- m=0 transition forbidden
- Splitting gives B field
- 11 parameters

\(2^3S-2^3P_2\)
- m=±1 transitions
- m=0 transition
- 2 crossovers
- 18 parameters
Experimental Resolution

\[ 2^3S - 2^3P_0 \]

\[ \nu_{01} = 2^3P_0 - 2^3P_1 \]

\( \sigma < 75 \text{ Hz in a few hours!} \) \rightarrow \text{Linesplitting up to 20000!}
## Systematics Overview

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Typical Size</th>
<th>Error (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B field measurement &amp; inhomogeneity</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Zeeman</td>
<td>1 MHz</td>
<td>10</td>
</tr>
<tr>
<td>AC Stark</td>
<td>1 kHz</td>
<td>75</td>
</tr>
<tr>
<td>RF Discharge Shifts</td>
<td>200 Hz</td>
<td>100</td>
</tr>
<tr>
<td>Linear Pressure</td>
<td>1 kHz</td>
<td>250</td>
</tr>
<tr>
<td>Light-Pressure</td>
<td>5-10 kHz</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Beam Misalignment</td>
<td>~20 kHz</td>
<td>1</td>
</tr>
<tr>
<td>Wavefront Curvature</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Velocity-Changing Collisions</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Self-focusing</td>
<td>&lt;20 kHz</td>
<td>???</td>
</tr>
</tbody>
</table>
Systematics: Linear Pressure Shifts

\[ \nu_{01} = 2^3P_0 - 2^3P_1 \]

\[ \sigma_y = 230 \text{ Hz} \]

\[ 2^3S - 2^3P_0 \]

\[ \sigma_y = 470 \text{ Hz} \]

slope = -1.666 (15) MHz/Torr

- optical frequencies
- intervals

Systematics: Light-Pressure Shifts

- Atomic recoil modifies velocity distribution

\[
N(v) = N_0(v) + N_0(v_0)\varepsilon_r\tau \frac{4Sk(v-v_0)\Gamma^3}{[k^2(v-v_0)^2 + \Gamma^2]^2}
\]

- Small (\(\varepsilon_r\tau \ll 1\)) asymmetric kink is superimposed on symmetric Lorentzian

\[
L(\Omega) = \frac{1}{2(\Omega^2 + 1)} + \varepsilon_r\tau \frac{\Omega}{(\Omega^2 + 1)^2} \approx \frac{1}{2} \frac{1}{\Omega - \varepsilon_r\tau}\]

- Corrected by comparing m=±1 and m=0 peaks of the \(2^3P_2\) lineshape
Systematics: Self-focusing

- Intensity-dependent index of refraction causes focusing of pump/probe beams
- Small asymmetric signal component ~ $D(\Omega)$
- Asymmetric component shifts Lorentzian frequency

Solutions:
1. Include $D(\Omega)$ in fits
2. Extrapolate to zero
   - pressure
   - laser power
   - RF discharge power

- optical frequencies
- intervals
Systematics: Beam Misalignment

- Radial flow of atoms
- Transverse velocity distribution is NOT a Maxwell-Boltzmann
- Residual Doppler shifts + broadening
- uncertainty = ±20 kHz

![Diagram of beam misalignment]

Center Frequency

- optical frequencies
- intervals 0
Future Outlook

TABLE I. Shifts and uncertainties that must be added to 2.291, 29.616, and 31.908 GHz, respectively.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>( f_{12} ) in kHz</th>
<th>( f_{01} ) in kHz</th>
<th>( f_{02} ) in kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercepts</td>
<td>176.36(37)</td>
<td>949.99(66)</td>
<td>125.58(84)</td>
</tr>
<tr>
<td>Light power</td>
<td>−0.96(16)</td>
<td>+1.20(12)</td>
<td>+0.78(19)</td>
</tr>
<tr>
<td>VCC</td>
<td>+0.00(30)</td>
<td>+0.00(15)</td>
<td>+0.00(30)</td>
</tr>
<tr>
<td>Discharge power</td>
<td>+0.19(09)</td>
<td>+0.47(12)</td>
<td>+0.42(24)</td>
</tr>
<tr>
<td>Typical Zeeman shift</td>
<td>−1188.43(00)</td>
<td>+471.60(00)</td>
<td>−716.83(00)</td>
</tr>
</tbody>
</table>


\( \sim 0.25 \text{ kHz} \)

0.06-0.08 kHz self-focusing

\( \nu_{12} \)

\( \nu_{01} \)

\( \nu_{02} \)

\( \alpha \) to 5 ppb!
Conclusions

• Theory
  – Two groups have calculated terms up to $\alpha^5$
  – Disagreement of ~3 kHz

• Experiment
  – Agreement to <1 kHz
  – Disagreement with theory between 8-20 kHz!
  – Source of disagreement: terms of $\alpha^6$?

• Harvard experiment
  – fine structure intervals to 300 Hz
  – 2-3X improvement over 2005 results
  – determines $\alpha$ to 5 ppb
  – 2S-2P optical measurements to 20 kHz