D_2 Hyperfine Structure of Rubidium Isotopes ^{87}Rb and ^{85}Rb

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8.14 Experimental Physics II
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Goal:

- Probe the hyperfine structure of atoms.
- Big problem: This structure is masked by Doppler broadening

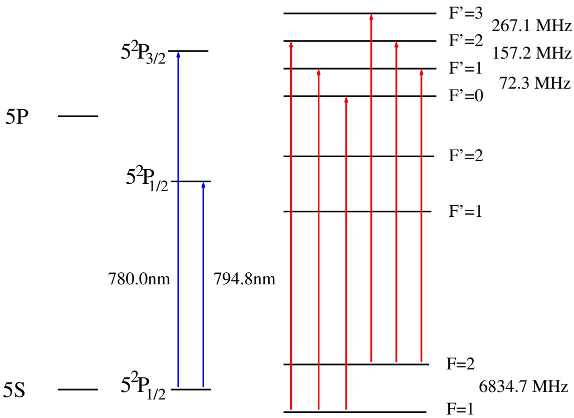
Outline

1. Introduction
   - Spectrum of ^{87}Rb
   - Magnetic Dipole Interactions
   - Electric Quadrapole Interactions
   - Hyperfine Structure and Crossover Resonances
2. Experimental
   - Doppler-Broadened Spectrum of ^{85}Rb and ^{85}Rb
   - Doppler-Free Saturation Setup
   - Fabry-Perot Calibration
   - Doppler-Broadened Spectrum of ^{85}Rb and ^{85}Rb
3. Results and Error Analysis
   - Hyperfine Spectrum of ^{85}Rb and ^{85}Rb
   - Error and Systematic broadening effects

- Electronic structure: [Kr]$5s^1$
- Perturbations break energy degeneracy to $n^{(2s+1)}L_j$
- Angular momentum coupling:

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$
$$\mathbf{F} = \mathbf{I} + \mathbf{J}$$

- ^{87}Rb ($I = 3/2$) and ^{85}Rb ($I = 5/2$)



$$\frac{\mathbf{p}^2}{2m} + Z_{\text{eff}}\frac{e^2}{r} \qquad -\mu \cdot \mathbf{B} \qquad H^{hf}_{magn} + H^{hf}_{quad}$$

- Parametrizing splitting with A,

$$H^{hf}_{magn} = -\mu_I \cdot \mathbf{B}_{el} =\longrightarrow A\mathbf{I} \cdot \mathbf{J} \tag{1}$$

- Good quantum numbers, $|ijfm_f\rangle$:

$$\Delta E = \frac{A}{2}\left[F\left(F+1\right) - J\left(J+1\right)F - I\left(I+1\right)\right] = \frac{A}{2}C \tag{2}$$

- Angular momentum selection rule: $\Delta F = 0, \pm 1$

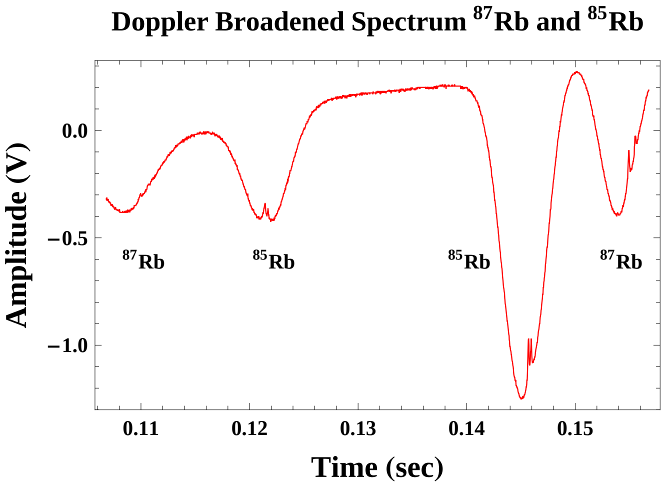
- Summing of nuclear electrical multipole moments:

$$\begin{aligned} H^{hf}_{quad} &= \frac{-e^2}{|r_e - r_n|} \\ &\to B\frac{3\left(\mathbf{I}\cdot\mathbf{J}\right)^2 + \frac{3}{2}\mathbf{I}\cdot\mathbf{J} - I\left(I+1\right)J\left(J+1\right)}{2I\left(2I-1\right)J\left(2J-1\right)} \end{aligned} \tag{3}$$

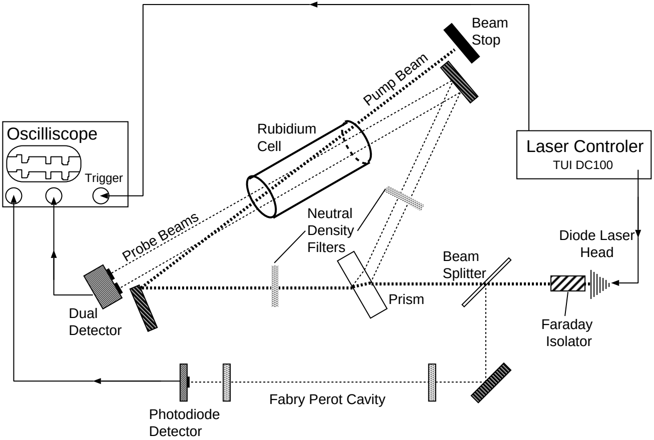
- B measures quadrapole interaction and vanishes for spherically charged distributions.

- Combined corrections yields:

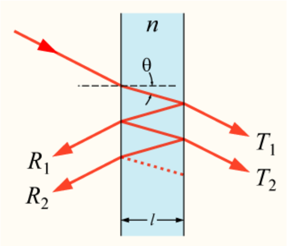
$$\Delta E_F = \frac{1}{2}AC + B\frac{\frac{3}{4}C\left(C+1\right) - I\left(I+1\right)J\left(J+1\right)}{2I\left(2I-1\right)J\left(2J-1\right)} \tag{4}$$

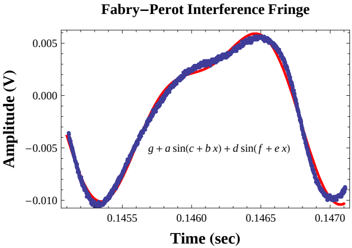


At 297K and 780nm, $\Delta\nu_{1/2} = 2\frac{\nu_0}{c}\sqrt{\frac{2k_B T \ln 2}{A}} \approx 502\mathrm{MHz}$ (640Mhz meas.)



Parameters: Alignment, power broadening, mode (diode current/temperature and scanning).



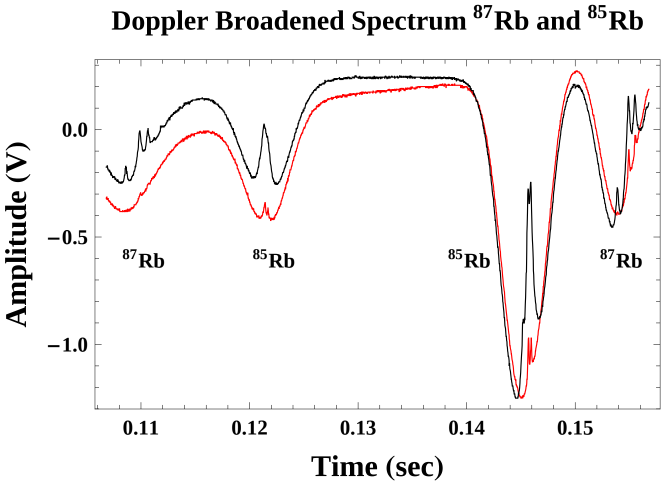


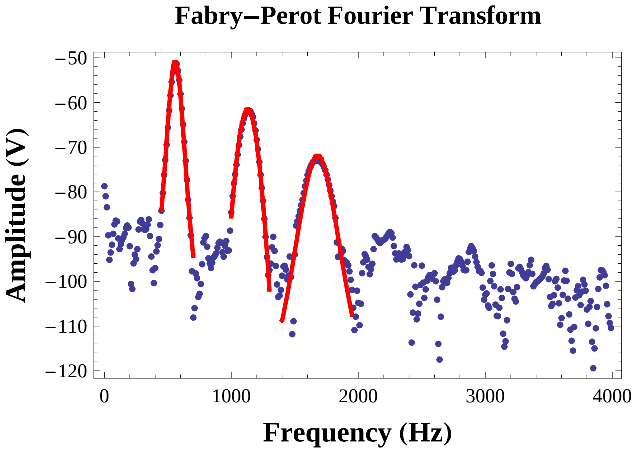
- Free spectral range calibrates relative frequency spacing in spectra:

$$\Delta\nu = \frac{c}{2n_{\mathrm{Air}}L\cos\theta} \qquad (5)$$

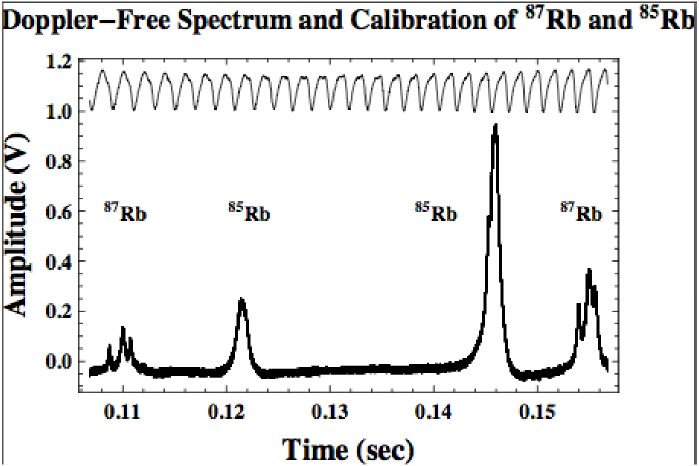
- Accounting for double mode, we measure FSR:

$$\Delta\nu = 214 \pm 2MHz \qquad (6)$$

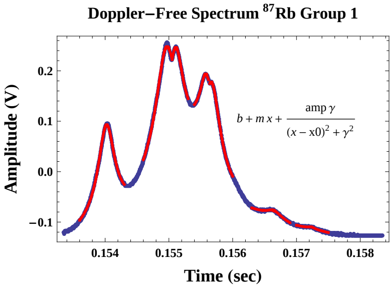

Doppler Broadened Spectrum ^{87}Rb and ^{85}Rb
Amplitude (V)
0.0
−0.5
−1.0
^{87}Rb
^{85}Rb
^{85}Rb
^{87}Rb
0.11
0.12
0.13
0.14
0.15
Time (sec)

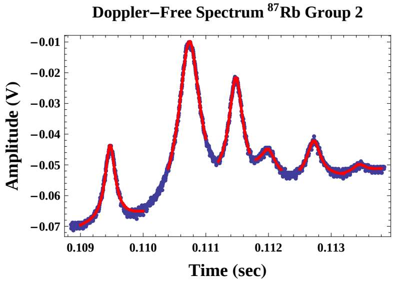


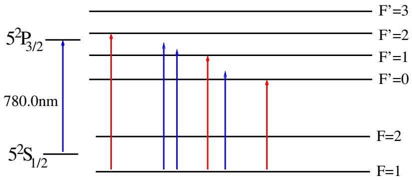
Center values at 1679.84 $\pm$ 4.15, 1129.29 $\pm$ 0.54, and 558.321 $\pm$ 0.88 Hz.

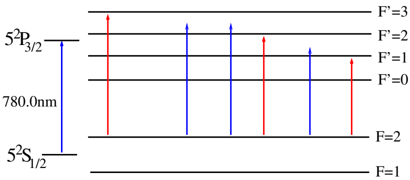


Natural linewidth: 6.065(9) MHz (14 ± 2MHz Meas.)


Doppler−Free Spectrum ^{87}Rb Group 1
Amplitude (V)
Time (sec)
$b + m\,x + \frac{\text{amp}\,\gamma}{(x - \text{x0})^2 + \gamma^2}$
0.2
0.1
0.0
−0.1
0.154
0.155
0.156
0.157
0.158


Doppler−Free Spectrum ^{87}Rb Group 2
Amplitude (V)
Time (sec)
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
0.109
0.110
0.111
0.112
0.113


$5^2P_{3/2}$
780.0nm
$5^2S_{1/2}$
F'=3
F'=2
F'=1
F'=0
F=2
F=1


$5^2P_{3/2}$
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F'=3
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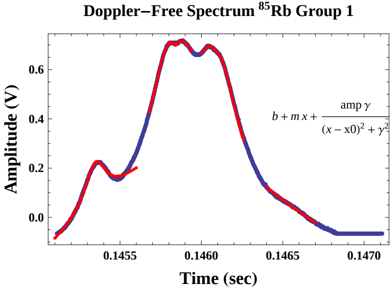
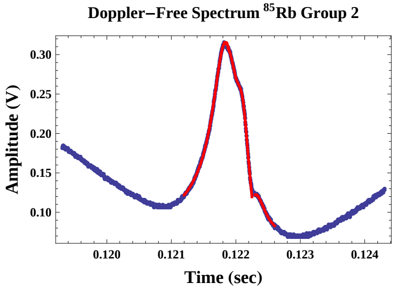
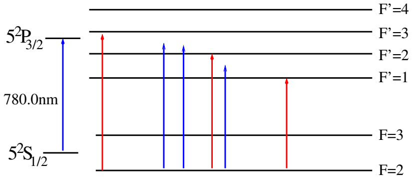
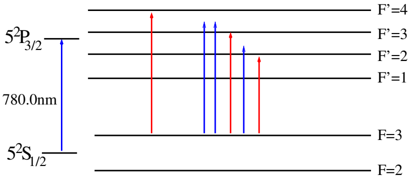

Doppler−Free Spectrum 85Rb Group 1
Amplitude (V)
Time (sec)
0.0
0.2
0.4
0.6
0.1455
0.1460
0.1465
0.1470
$b + m x + \frac{\text{amp}\,\gamma}{(x - \text{x0})^2 + \gamma^2}$


Doppler−Free Spectrum 85Rb Group 2
Amplitude (V)
Time (sec)
0.10
0.15
0.20
0.25
0.30
0.120
0.121
0.122
0.123
0.124


$5^2P_{3/2}$
780.0nm
$5^2S_{1/2}$
F'=4
F'=3
F'=2
F'=1
F=3
F=2


$5^2P_{3/2}$
780.0nm
$5^2S_{1/2}$
F'=4
F'=3
F'=2
F'=1
F=3
F=2

- Missing peaks characterized by crossover resonances:

$$\nu_1 = \nu_c - \frac{\nu_{z1}}{c}\nu_c \qquad \text{and} \qquad \nu_2 = \nu_c + \frac{\nu_{z1}}{c}\nu_c \tag{7}$$

and adding,

$$\nu_c = \frac{\nu_1 + \nu_2}{2} \tag{8}$$

- Between states with common ground states, separated less than Doppler linewidth.

Table: Classification of hyperfine structure for ^{87}Rb and ^{85}Rb isotopes.

Transition	$\Delta\nu$(MHz)	$\Delta\nu$(MHz)
$5^2P_{3/2}\,(F = 3, 2)$	266.650 (9)	268.0 ± 2.0
$5^2P_{3/2}\,(F = 2, 1)$	156.947 (7)	155.0 ± 5.7
$5^2P_{3/2}\,(F = 1, 0)$	72.218 (4)	65.3 ± 7.0
$5^2S_{1/2}\,(F = 2, 1)$	6834.68 (3)	6712.9 ± 167.5
$5^2P_{3/2}\,(F = 3, 2)$	121	110.8 ± 8.8
$5^2P_{3/2}\,(F = 2, 1)$	63	67.7 ± 4.1
$5^2P_{3/2}\,(F = 1, 0)$	29	32.7 ± 3.0
$5^2S_{1/2}\,(F = 2, 1)$	3036	2905.96 ± 115.3

- Error in calibration (Fabry Perot: $\pm$0.4cm, multimode).
- Instrumental uncertainty (5-10mV).
- Systematic line broadening in peaks:

$$\gamma = \frac{1}{\tau} + \frac{2}{T} + 2\pi\delta_{\text{laser}} + \dots \tag{9}$$

  - Natural (10^6Hz)
  - Collision ($3 \cdot 10^3 - 3 \cdot 10^6$Hz)
  - Wall-collision ($10^3 - 10^4$Hz)
  - (Laser) power ($10^4 - 10^5$Hz)

Summary

- Error analysis: Data agrees qualitatively.
- 2nd set of variable neutral density filters might be useful.