Optical Pumping of Rubidium Vapor

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Outline

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Introduction

• Exploration of radio-frequency region of atomic spectra useful for studying details of atomic structure.

• Kastler devised a new method of radio-wave spectroscopy.

• Optical pumping: technique of using visible light to raise individual atoms from lower to higher states of internal energy.

• Practical applications: the maser, the laser, magnetometers.
Motivation

• Observe resonant radiofrequencies in Rb-87 and Rb-85.

• Measure ambient magnetic field of Earth.

• Determine ratio and values of Lande g-factors for two isotopes of Rb.
• Rb pumping: due to circularly polarized light, every transmitted photon has an energy of $\pm \hbar$, transitions in the Rb atoms have $\Delta m_f = 1$.

• Spontaneous transitions can occur with $\Delta m_f = \pm 1, 0$.

• Atoms landing in $m_f = +1$ states remain there.
The Landé g-factor

• Geometric factor from magnetic interaction: \( \vec{\mu} = g_f \frac{e}{2m} \vec{F} \).

• Landé g-factor \( g_J \) for fine structure interaction comes from spin-orbit coupling: \( E_{fs} = \frac{e}{2m} \vec{B} \cdot \vec{L} + 2\vec{S} \).

• At small \( \vec{B} \), fine structure dominates, use \( |n, l, j, m_j \rangle \) basis.
  – \( \vec{L} \) and \( \vec{S} \) precess rapidly about \( \vec{J} \); project \( \vec{S} \) on \( \vec{J} \).
  – Obtain \( \langle \vec{L} + 2\vec{S} \rangle = g_J \vec{J} \).

• To obtain \( g_f \), take into account magnetic moment of nucleus:
  \( E_{hf} = \frac{e}{2m} \vec{B} \cdot (g_J \vec{J} + g_I \vec{I}) = g_f m_f \mu_B \vec{B} \).
Theoretical Values of Landé $g$ factors

\[ g_J = 1 + \frac{j(j+1) + s(s+1) - l(l+1)}{2j(j+1)} \]

\[ g_f = g_J \left[ \frac{f(f+1) + j(j+1) - i(i+1)}{2f(f+1)} \right] \]

\[ g_J(Rb^{85}) = 2, \quad g_J(Rb^{87}) = 2 \]

\[ g_f(Rb^{85}) = -\frac{1}{2}, \quad g_f(Rb^{87}) = -\frac{1}{3} \]
Optical Pumping Setup

- Rubidium Lamp
- Linear polarizer
- Half wave plate
- Narrow-band filter
- Rubidium cell
- Helmholtz coils
- Focusing lens
- Collimating lens
- Photodiode
- Current to Voltage Amplifier
- Oscilloscope
- Function Generator
- Coil current supply
- to RF coils
- to Trigger
Relation between $\vec{B}$ and $f$

- $f = \frac{g_F \mu_B}{h} \vec{B}$

- $|\vec{B}| = \sqrt{B_x^2 + B_y^2 + B_z^2}$

- Varied $\vec{B}_{HC} = \frac{8\mu_0 N \vec{I}}{\sqrt{125R}}$

- $f = \frac{g_F \mu_B}{h} \frac{8\mu_0}{\sqrt{125}} \sqrt{B_x^2 + B_y^2 + B_z^2}$

- Fit line used for $I_x$ and $I_y$: $y = \frac{b}{a} \sqrt{c^2 + x^2 + d}$
Hyperbola Fit to Varying X Current

Resonance frequency minimum located at:
\[ I_x = (104.1 \pm 0.2) \text{ mA} \]
\[ \chi^2_{v-1} = 1.2 \]

Hyperbola Fit to Varying Y Current

Resonance frequency minimum located at:
\[ I_y = (-14.4 \pm 1) \text{ mA} \]
\[ \chi^2_{v-1} = 1.6 \]
Linear Fit to Varying Z Current

Line intersections:

[Rb$^{85}$]: $I_z = (24.01 \pm 0.76)$ mA

[Rb$^{87}$]: $I_z = (24.05 \pm 0.62)$ mA

Average: $I_z = (24.03 \pm 0.51)$ mA
Data Analysis

- For x- and y- directions, obtained value for current that resulted in a minimum resonant frequency.

- For z-direction, obtained intercept of two lines.

- Used equation for $\vec{B}$ created by Helmholtz coils to calculate value necessary to cancel out Earth’s $\vec{B}$:

$$\vec{B}_{HC} = \frac{8\mu_0NI}{\sqrt{125R}}$$ (1)
Error Analysis

- \( I_z = \frac{a_{r1} - a_{l1}}{a_{l2} - a_{r2}} \)

- Error in \( I_z \): \( \sigma = \sqrt{I_z [\frac{\sigma_{r1}^2 + \sigma_{l1}^2}{(a_{r1} - a_{l1})^2} + \frac{\sigma_{l2}^2 + \sigma_{r2}^2}{(a_{l2} - a_{r2})^2}]} \)

- Error in \( B \) components: \( \sigma_B = \sqrt{B^2 (\frac{\sigma_I^2}{I^2} + \frac{\sigma_R^2}{R^2})} \)

- Random Error: fluctuations in values on oscilloscope, errors in fit parameters.

- Additional unaccounted systematic error?
Results

• Calculated ratio between the $g_f$s of Rb$^{87}$ and Rb$^{85}$, using location of two resonant peaks: $1.49 \pm 0.01$.

• Calculated $g_f = \frac{h f}{B_z \mu_B}$ for both Rb isotopes, compared to theoretical calculation.

  – Expt.: $g_f(Rb^{85}) = 0.319 \pm 0.001$, $g_f(Rb^{87}) = 0.520 \pm 0.001$
  – Theory: $g_f(Rb^{85}) = \frac{1}{3}$, $g_f(Rb^{87}) = \frac{1}{2}$

• Calculated $|\vec{B}|$ of the Earth: $(294.1 \pm 21.1)$ mgauss, measured to be $\approx 300$ mgauss, actual value $\approx 600$ mgauss.
Conclusions

- Observed good agreement between experiment and theory in ratio and values of $g_f$ for Rb$^{87}$ and Rb$^{85}$; $0.520 \pm 0.001$ and $0.319 \pm 0.001$ respectively, compared to $\frac{1}{2}$ and $\frac{1}{3}$.

- Correct order of magnitude for $|\vec{B}|$ of Earth.

- Improvement: to measure Earth’s field more accurately, need less interference.