Physics 111B: [Optical Pumping]

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In the field of optical pumping (OPT), we present an experimental apparatus for observing atomic structures and how they're affected by the presence of an external magnetic field. The study of optical pumping is an application of several concepts from quantum mechanics (e.g. hyperfine structure, optical polarization, selection rules, etc.). This lab particularly investigates the Zeeman splitting of ^{85}Rb and ^{87}Rb atoms caused by an ambient and applied magnetic fields. The goals in this experiment are to observe the optically detected magnetic resonances and determine the nuclear spins for both isotopes, measure the ambient magnetic field, and illustrate the linearity between current and frequency at resonance.

I. INTRODUCTION AND BACKGROUND

This optical pumping lab can be contextualized as an application of several fundamental concepts that stem from quantum mechanics and electromagnetism. We will learn how properties of atoms (e.g. position, spin, etc.) are represented as quantum states. Spectroscopic evaluation of quantum states allows us to illustrate the structure of atoms and measure the selective energy levels that govern subatomic interactions. While a major part of this lab is understanding how magnetic fields affect atomic structure, concepts like quantum numbers for electron orbitals, conservation of angular momentum, and the energy of magnetic dipoles in magnetic fields will all come to light.

A. Rubidium Atom Structure

The focus of this experiment is two isotopes of Rubidium (Rb): ^{85}Rb and ^{87}Rb. Since ^{85}Rb is more abundant than ^{87}Rb, ^{85}Rb and ^{87}Rb will be referred to as the major and minor isotope respectively. Rb is alkali-metal atom with 1 valence electron in the 5s orbit. This valence electron can jump to the 5p excited state if it absorbs a photon with enough energy (1.6eV).

Atoms have an electron orbital angular momentum (L), electron spin (S), and nuclear spin (I). Both Rb isotopes in the ground state have L = 0 and S = $\frac{1}{2}$. However, their nuclear spins are different: $I_{85} = \frac{5}{2}$ and $I_{87} = \frac{3}{2}$.

The structure of atoms and the order of splitting depends on several factors. The first-order splitting (fine structure) is caused by the relativistic effects that couple both the electron orbital angular momentum and electron spin. The ground 5s state does not split but the excited 5p state into the $2P_{\frac{1}{2}}$ and $2P_{\frac{3}{2}}$. The transition from 5s $\rightarrow 2P_{\frac{1}{2}}$ is called the D1 line (795nm) and the 5s $\rightarrow 2P_{\frac{3}{2}}$ transition is the called the D2 line (780nm).

The interactions between the the electron orbital angular momentum and nuclear spin cause the second-order splitting (hyperfine structure). Since the magnetic moments between the nuclei and electrons are different, the hyperfine splitting is significantly smaller than the fine structure splitting.

Before a magnetic field is applied to the atom, the total angular momentum is denoted as:

$$F = I + J \tag{1}$$

where

$$J = L + S \tag{2}$$

B. Magnetic Fields and the Breit-Rabi Formula

In the case of ground state ^{87}Rb, eight distinct quantum states can be labelled as $|J, I; m_J, m_I >$ where $m_J \in [\pm\frac{1}{2}]$ and $m_I \in [\pm\frac{1}{2}, \pm\frac{3}{2}]$ represent magnetic quantum numbers.

To describe the energy eigen states and eigenvalues of an atom, we can use the hyperfine Hamiltonian:

$$H_{hfs} = -\mu_I(B_J + B_{ext}) - \mu_J B_{ext} \tag{3}$$

where μ_I and μ_J are magnetic dipole moments. These dipole moments can be further represented as:

$$\mu_I = g_I \mu_N I \tag{4}$$

where

$$\mu_N = \frac{e\hbar}{2m_e} \tag{5}$$

and

$$\mu_J = g_J \mu_B J \tag{6}$$

where

$$\mu_B = \frac{e\hbar}{2m_e} \tag{7}$$

where m_e is the mass of the electron and m_p is the mass of the proton.

The coupling of nuclear and electronic angular momenta is described by:

$$-\mu_I B_J = AhIJ \tag{8}$$

and an externally applied magnetic field is represented by:

$$-(\mu_I + \mu_J)B_{ext} \tag{9}$$

This finally gives up the relationship between the B_{ext} and the splitting of neighboring Zeeman states:

$$\frac{\nu}{B_{exp}} = \frac{2.799}{2I+1}\frac{MHz}{G} \tag{10}$$

where ν is the is the resonant frequency and I depends on the isotope.

C. Optical Pumping

When an electron in a lower-energy state absorbs energy (i.e. a photon of frequency ν), the electron is brought to a higher energy state $|F, m_F + 1 >$ proportional to ν. This also generates spin polarization due to how irradiation of circularly polarized light transfers angular momentum and changes their magnetic quantum numbers. Since the electron cannot go to a higher energy state, the electron will decay to ground state $|F, m_{F,+1} - 1 >$ or $|F, m_{F,+1} + 0 >$. Since electrons in the ground state $|F, m_{F,+1} - 1 >$ will continue to absorb energy and decay, the final state of the electrons is the $|F, m_{F,+1} + 0 >$ state; this is the process of optical pumping. To quantify the population in the initial (1) and final (2) states, we have the expression:

$$\frac{P_2}{P_1} = exp(-\frac{E_2 - E_1}{k_B T}) \tag{11}$$

where $E_2 - E_1$ is the energy difference between the states and $k_B T$ is the normal Boltzmann distribution for the population. In the pumped state, $P_2 >> P_1$.

If the light propagates in the Z - direction, then the pumped state will be the highest energy level in the ground state, while in the -Z - direction the pumped state will be the lowest energy level in the ground state. The pumped state is also known as the "dark state" because the Rb atoms no longer absorbs the optical light. In this experiment, we are mainly concerned with the D1 transitions for both isotopes.

D. Optically Detected Magnetic Resonance

When the dark state in the Rb atom is reached, we can observe radio-frequency (RF) magnetic transitions. When the RF is not in resonance, all electrons are pumped into the final state, causing the gas to be transparent. However, when the RF is in resonance, the atoms are driven out of the pumped state, allowing absorption to occur (i.e. gas is a opaque) and the signal is at a minimum. When the photodiode detects a lower light level, optically detected magnetic resonance (ODMR) is achieved.

II. EXPERIMENTAL PROCEDURES

A. Equipment

The instruments used in this experiment are the SRS DS 345 Signal Function Generator, SR560 Amplifier, HP 3478A Multimeter, HP E3615A DC Power Supply, Tektronix 2225 Oscilloscope, and an oven heater.

The block diagram for the experiment is shown in 1. The Rb gas is vaporized using teh heater and then irradiated with a circularly polarized lamp, the RF is controlled by the function generator, and the signal is detected with a photodiode that connects to the oscilloscope. The Helmholtz coils are controlled by the DC power supply and used to control the external magnetic field.

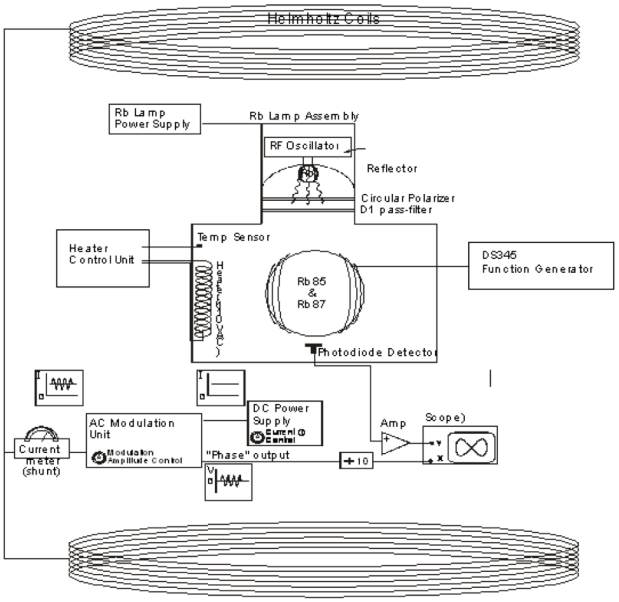

FIG. 1. The block diagram for the OPT experiment.

B. Ideal Bulb Temperatures

Each isotope needs to be vaporized to an ideal temperature where ODMR is best observed. To find the ideal temperatures: heat up the Rb glass cell to 55°K, sweep the RF to observe ODMR signal, track the relative amplitude of the ODMR signal as the cell cools down. The

peaks of the curves in Figure 3 illustrates the ideal temperatures for both isotopes.

The ideal temperatures we found were 45°K for ^{85}Rb and 48°K for ^{87}Rb. These temperatures were maintained throughout the process of taking data for our experiment (depending on the isotope).

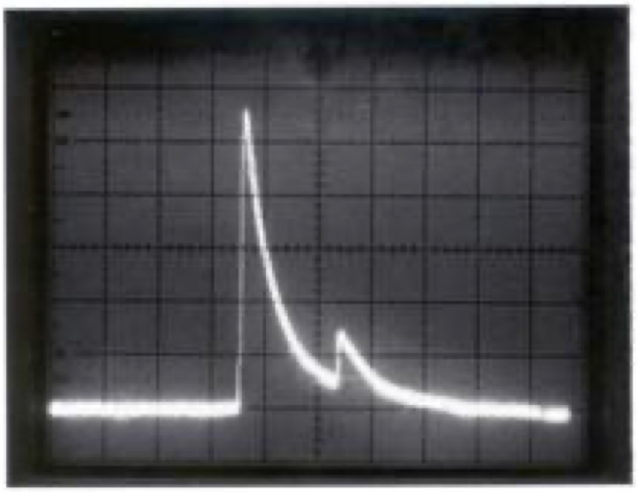

FIG. 2. Observations of ODMR where the x-axis is the swept RF and the y-axis is the photodiode signal.

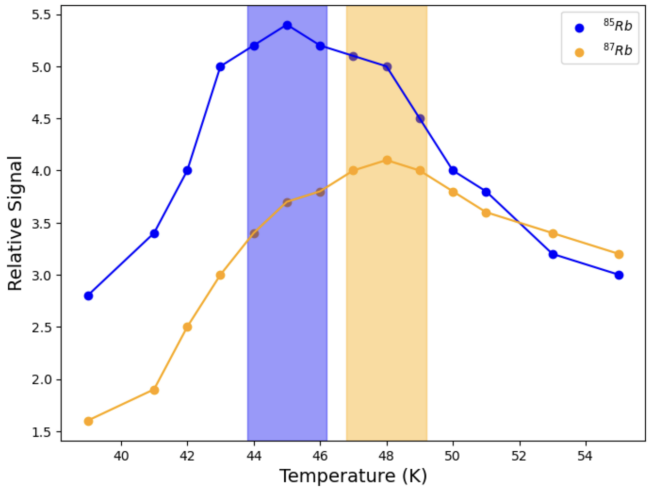

FIG. 3. Plot of relative ODMR signal amplitude vs. temperature.

C. Current Modulation/Lock-in Detection Method

Instead of varying the RF, a more precise and accurate method for observing the Zeeman resonance frequency is to modulate the current running the Helmholtz coils and apply a static RF field. The data that my partner and I took was each of the currents modulated and the corresponding RF.

For each modulated current, corresponding RFs were found by identifying when ODMR was observed. This occurs when the oscilloscope (with the modulation output on the x-axis and photodiode signal on the y-axis) displays a Lissajous curve (seen in Figure 4). The Lissajous curve is produced because the corresponding RF puts the isotope in resonance as the Helmholtz current (i.e. magnetic field) modulates around some current. The term "lock-in" refers to how the Lissajous curve is locked-in at resonance.

The current modulation/lock-in detection method is repeated for both isotopes, various modulating currents amplitudes and directions, and RF fields.

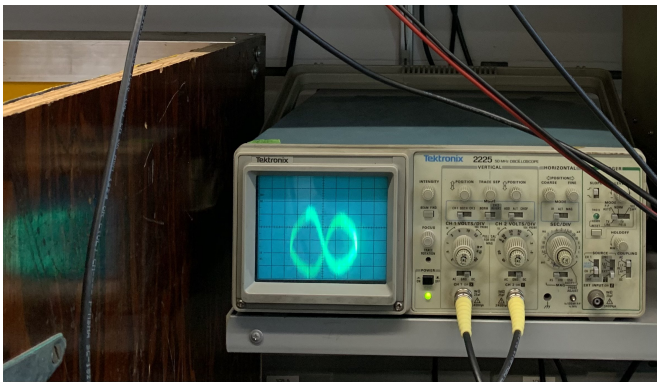

FIG. 4. Example of a Lissajous curve, observed when the system is in resonance with a modulated current and RF.

III. RESULTS & ANALYSIS

A. Frequency vs. Current

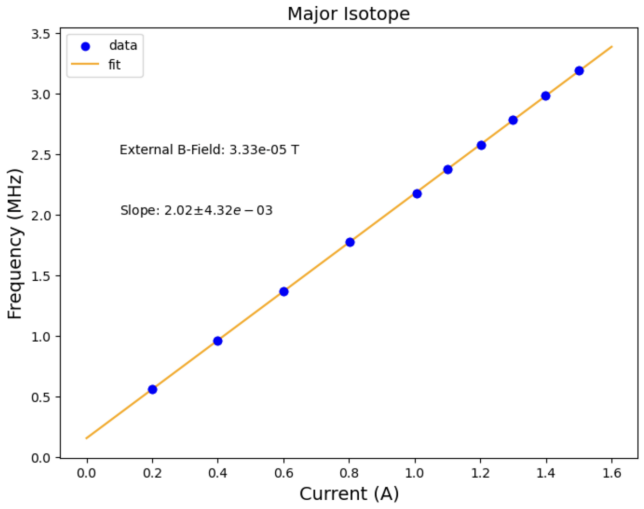

FIG. 5. Frequency vs. current plot for major isotope.

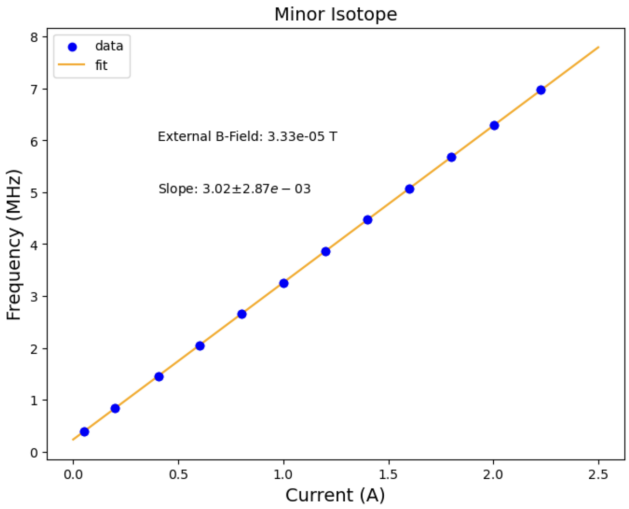

FIG. 6. Frequency vs. current plot for minor isotope.

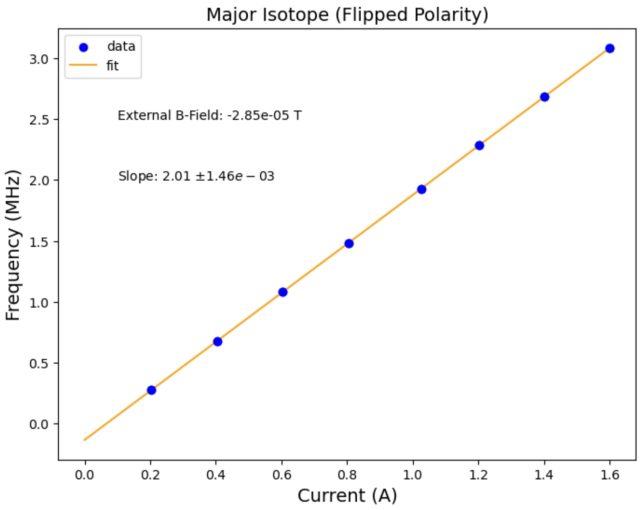

FIG. 7. Frequency vs. current plot for major isotope and flipped polarity.

The RF vs. Helmholtz current for the different isotopes and polarities can be seen in Figures 5 - 8. I used a linear model for my data because the χ^2 were quite small. For all of the plots, we sampled current from within the range of 0.05A - 2.4A; currents that were small made it hard to detect the RF, while currents that were too high oversaturated the signal. Since each RF was measured when the Lissajous curve looked as symmetric as possible, we measured an error for each point by observing when the Lissajous curve is noticeably asymmetric. Our error bars are on the order of $\frac{1}{1000}MHz$, meaning they are smaller than the figures' data points themselves.

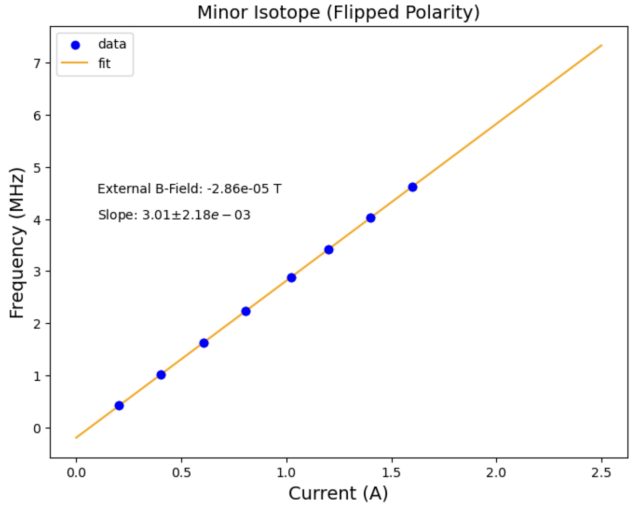

FIG. 8. Frequency vs. current plot for minor isotope and flipped polarity.

B. $\frac{\nu_{85}}{\nu_{87}}$ and Nuclear Spin

The value of the $\frac{\nu_{85}}{\nu_{87}}$ can be measured two ways. The first method is by using the Breit-Rabi formula and solving for the frequencies with two different isotopes. This is allows us to measure $\frac{\nu_{85}}{\nu_{87}} = \frac{2}{3}$. The other method is recognizing that RF vs. current can be modelled as a linear function, where the ν is the slope. With this method: $\frac{\nu_{85}}{\nu_{87}} \approx \frac{2.02}{3.02} \pm 5.19e-3$

The nuclear spin of each isotope can be measured by when we consider the external magnetic field is a sum of Helmholtz coil and ambient magnetic field. We have the equation:

$$B_{ext} = (0.9x10^{-2})\frac{Ni}{a} + B_{ambient} \tag{12}$$

where N = 135 turns and A = 0.275m. We can then plug this into the Breit-Rabi formula and use the data for some current and it's corresponding RF to solve for I:

$$I = 0.5(\frac{2.799}{\nu}(4.418i + B_{ambient}) - 1) \tag{13}$$

We measured $I_{85} = 2.58 \pm 0.045$ and $I_{87} = 1.54 \pm 0.004$, which are close to the actual nuclear spins.

C. Ambient Magnetic Field

One way to find ambient magnetic field can be determined measuring the y-intercepts of the RF vs. current plots. The ambient magnetic fields measured with the major isotope was 3.33e-1 ± 4.49e-3 G and the minor isotope was 3.33e-1 ± 2.87e-3 G. When we flipped polarity, our values interestingly dropped 2.86e-1 G. We were unsure why this was the case; we theorize that it could be due to hysteresis when sampling polar currents.

Another way of finding the ambient magnetic field is by modulating a non-existent current measuring the RF with the lock-in method, and plugging it into the Breit Rabi equation. This method works because the modulation can still shake the ambient magnetic field, such that the gas can still be optically pumped. We were able to measure an ambient magnetic field of 0.348e-1 G; we expect that there is a lot of error coming from how the ambient magnetic field from the earth and room is dynamic.

D. Pumping Timescale

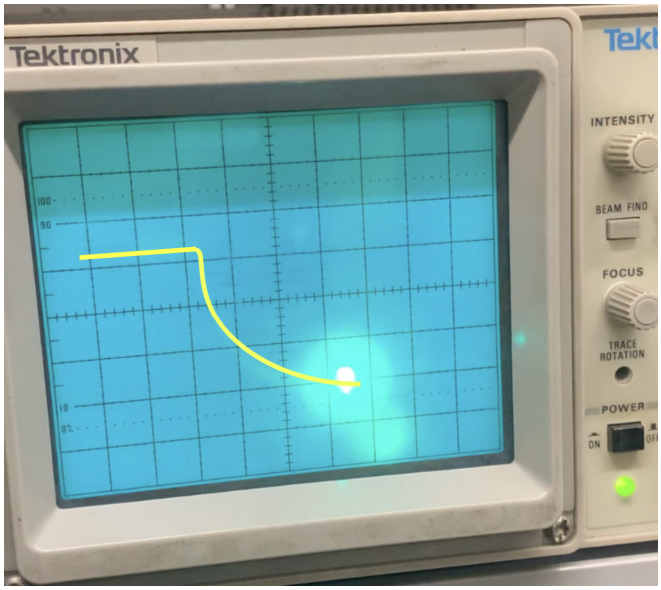

FIG. 9. Timescale for which Rb atom is pumped from initial to final (dark) state.

The timescale to which the state goes from initial to final (pumped) state can be measured by modulating the RF. This is represented in Figure 9. With each division on the oscilloscope representing 0.1 seconds, we estimate a pumping timescale of $\approx 0.3s$, which is close to the value of $\frac{1}{e}$.

IV. CONCLUSION

In this lab, we illustrated the quantum interactions that are necessary to observe optical pumping. We also measured important quantities like the nuclear spin of Rb atoms and the lab's ambient magnetic field. The errors in this experiment could've been measured in several different ways (e.g. my partner and I observing the Lissajous curve symmetry independently), but I believe our method worked well. Overall, fun experiment with important application to several physical fields. Thank you GSI's and staff for a great semester!