Optical Pumping

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Physics 111B, Spring 2020

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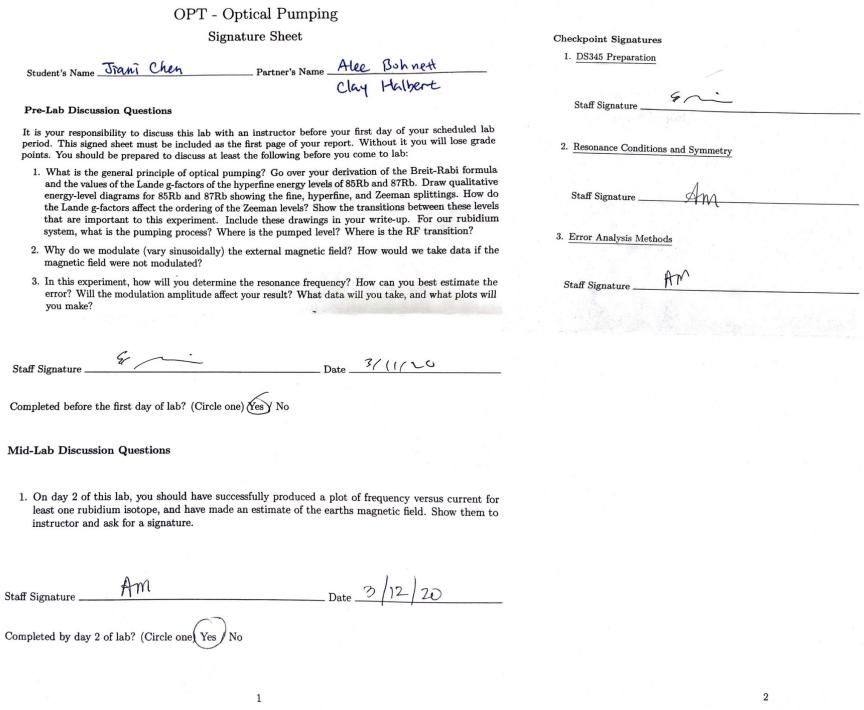

OPT - Optical Pumping

Signature Sheet

Student's Name Jiani Chen Partner's Name Alec Bohnett, Clay Halbert

Pre-Lab Discussion Questions

It is your responsibility to discuss this lab with an instructor before your first day of your scheduled lab period. This signed sheet must be included as the first page of your report. Without it you will lose grade points. You should be prepared to discuss at least the following before you come to lab:

1. What is the general principle of optical pumping? Go over your derivation of the Breit-Rabi formula and the values of the Lande g-factors of the hyperfine energy levels of 85Rb and 87Rb. Draw qualitative energy-level diagrams for 85Rb and 87Rb showing the fine, hyperfine, and Zeeman splittings. How do the Lande g-factors affect the ordering of the Zeeman levels? Show the transitions between these levels that are important to this experiment. Include these drawings in your write-up. For our rubidium system, what is the pumping process? Where is the pumped level? Where is the RF transition?
2. Why do we modulate (vary sinusoidally) the external magnetic field? How would we take data if the magnetic field were not modulated?
3. In this experiment, how will you determine the resonance frequency? How can you best estimate the error? Will the modulation amplitude affect your result? What data will you take, and what plots will you make?

Staff Signature _____ Date 3/11/20

Completed before the first day of lab? (Circle one) Yes / No

Mid-Lab Discussion Questions

1. On day 2 of this lab, you should have successfully produced a plot of frequency versus current for least one rubidium isotope, and have made an estimate of the earths magnetic field. Show them to instructor and ask for a signature.

Staff Signature AM Date 3/12/20

Completed by day 2 of lab? (Circle one) Yes / No

1

Checkpoint Signatures

1. DS345 Preparation

Staff Signature _____

2. Resonance Conditions and Symmetry

Staff Signature AM

3. Error Analysis Methods

Staff Signature AM

2

Figure 1: Signatures

Abstract

The spectroscopy technique of optical pumping allows us to perform difficult measurements such as the nuclear spin, resonant frequencies, relaxation times of isotopes, and also the Earth's magnetic field. It demonstrates an example of the interaction between light and matter. Rubidium vapor is a suitable source to used for optical pumping because its single free electron in the valence shell and its energy structure. In this experiment, circularly polarized light is used to pump the energy levels of Rubidium vapor. Using magnetic fields and radio-frequency modulations, we can analyze the rubidium vapor at resonance. Using the measurements at resonance, we can perform a linear fit to determine the nuclear spin and the strength of Earth's magnetic field.

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1 Introduction

Optical pumping is a spectroscopy technique used to study atomic energy states by pumping atoms from low energy to higher energy states. In this experiment, electromagnetic radiation is used to excite Rubidium isotopes (85 and 87) creating a population difference of excited states to low energy states. This process known as population inversion exceeds a difference many times more than the Maxwell-Boltzmann difference. This powerful technique allows us to study fundamental principles of quantum mechanics such as energy splitting and the electron spin resonance. By determining the resonant frequency of radio frequency (RF) signal, we can find the nuclear spins of the isotopes and the local magnetic field.

2 Theory

2.1 Electron Structure

Energy splitting in the electron energy structure occurs at the level of fine, hyperfine, and Zeeman splitting in decreasing magnitude. Fine structure splitting occurs from spin-orbit interactions characterised by the $^2P_{1/2}$ and $^2P_{3/2}$ energy states. Hyperfine structure arises from the spin of the nucleus and the angular momentum of the electron. And lastly Zeeman splitting is due to the distortion of the electron orbital causes by the interaction between the magnetic dipole moment and an external magnetic field.

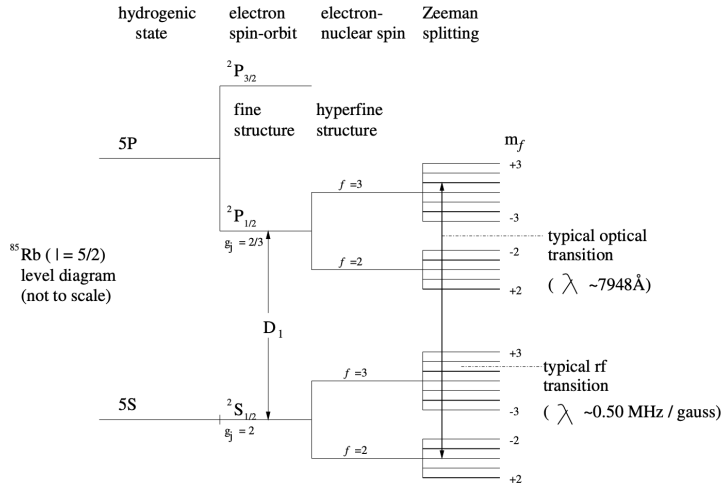
Our main focus is on the nuclear structure of Rubidium vapor under the condition that it is treated as an isolated system with a single valence electron in the outer shell. Such a system have a total angular momentum $\mathbf{F}^2 = (\mathbf{I} + \mathbf{J})^2$ where $\mathbf{I}$ is the nuclear angular momentum and $\mathbf{J}$ is the combination of the spin and orbital angular momenta of the electrons. The quantization number F can take on values of $F = I + J, I + J - 1, \ldots, |I - J|$. Because $\mathbf{J}$ is a much weaker interaction between the magnetic moments, it causes $\mathbf{I}$ and $\mathbf{J}$ to precess very slowly. The magnetic moment with angular momentum $\mathbf{F}$ is given by

$$\mu = g_f \frac{e}{2m} \mathbf{F}$$

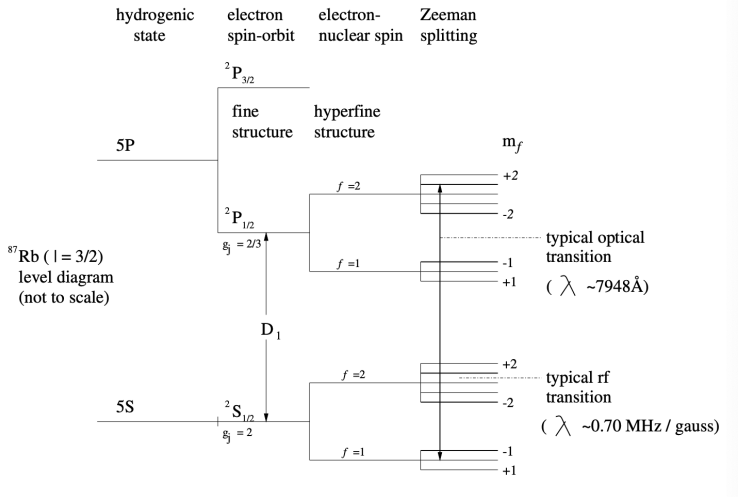
where g_f is a dimensionless constant called the Lande g factor. In the presence of a weak magnetic field $\mathbf{B}$, the degeneracy in the hyperfine structure is lifted leaving magnetic substates or Zeeman splitting. The g factor has an important consequence on the energy ordering of the Zeeman splitting levels. If g_F is negative, the Zeeman

energy quantum numbers m_F become reversed in order where the highest energy state takes on a $m_F < 0$ and the lowest energy state takes on a $m_F > 0$. (Refer to figure 2).

We can determine the hyperfine energy substates using the allowed quantum states. The angular momentum quantum numbers of Rubidium are $I = 5/2$ for ^{85}Rb and $I = 3/2$ for ^{87}Rb. The fine structure of the 2P orbital of rubidium can be split into $^2\mathrm{P}_{1/2}$ and $^2\mathrm{P}_{3/2}$. For $^2\mathrm{P}_{1/2}$ ($J = 1/2$), there are only two hyperfine splitting with values of $F = 2, 3$ for ^{85}Rb and $F = 1, 2$ for ^{87}Rb. For $^2\mathrm{P}_{3/2}$ ($J = 3/2$), we have $F = 0, 1, 2, 3$. The energy diagram of each energy splitting of rubidium is depicted in figure 2 [2].

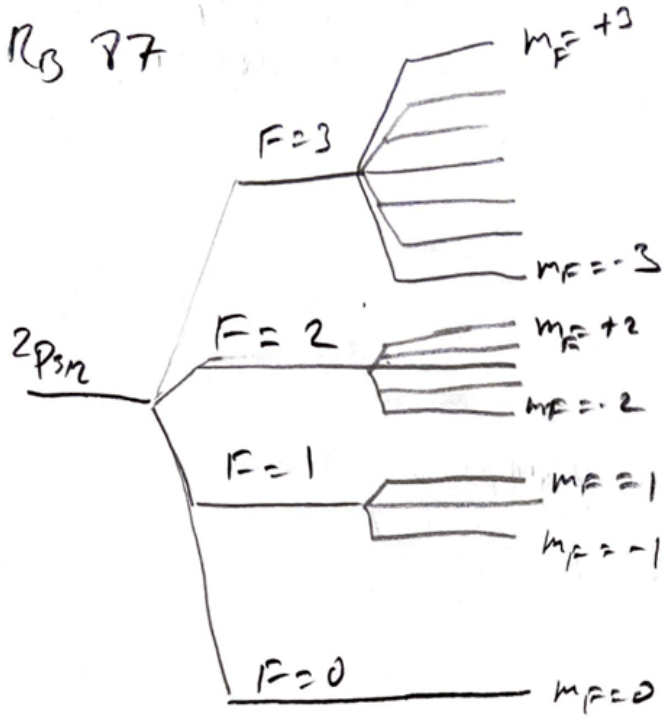


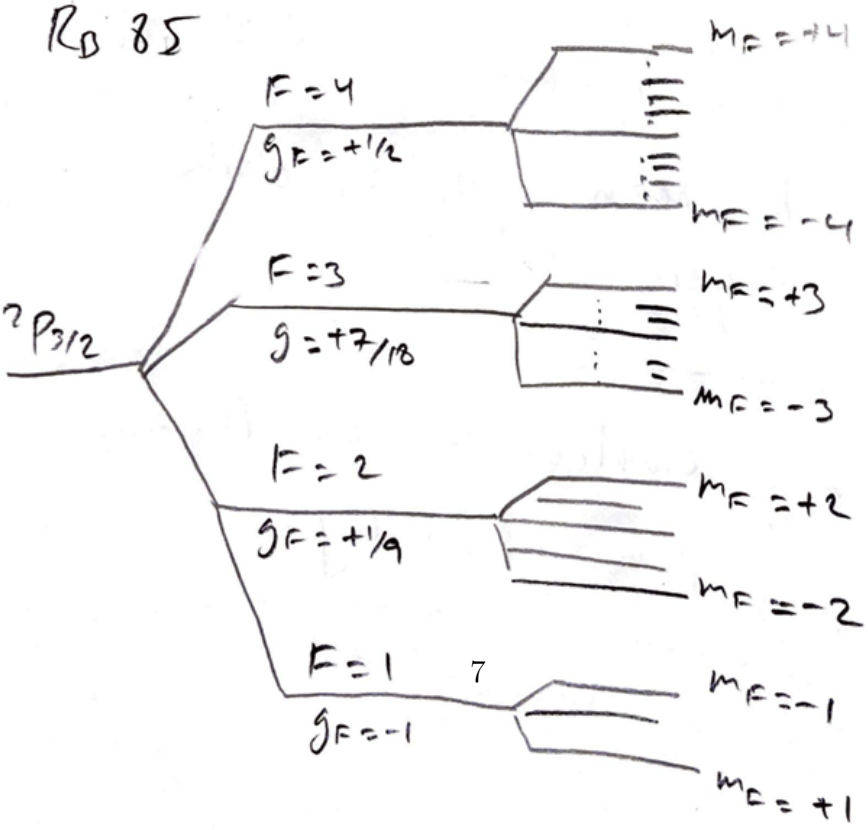
(a) rb85



(b) rb87

Figure 2: Energy Diagram of fine and hyperfine splittings of ^{85}Rb (top) and ^{87}Rb (bottom).


Rb 87
$m_F = +3$
F = 3
$m_F = -3$
$^2P_{3/2}$
F = 2
$m_F = +2$
$m_F = -2$
F = 1
$m_F = 1$
$m_F = -1$
F = 0
$m_F = 0$


Rb 85
$m_F = +4$
F = 4
$g_F = +1/2$
$m_F = -4$
F = 3
$m_F = +3$
$^2P_{3/2}$
$g = +7/18$
$m_F = -3$
F = 2
$m_F = +2$
$g_F = +1/9$
$m_F = -2$
F = 1
$m_F = -1$
$g_F = -1$
$m_F = +1$

2.2 Optical Pumping

Optical pumping is a process where under photon absorption, the population of energy level is highly dominated by a higher energy state as compared to the lower energy states in the Boltzmann distribution. In this experiment, Rubidium is irradiated with circularly polarized light in a magnetic field to create $5S_{1/2}$ to $5P_{1/2}$ energy transitions. After the atoms are excited to a higher energy state, they spontaneously decay a lower energy state with the only allowed transition of $\Delta\mu_f = 1$. This net result creates a "pumping" of the atoms in the $5S$ magnetic substate with positive μ_f [3]. The energy transition schematic can be seen in figure 4.

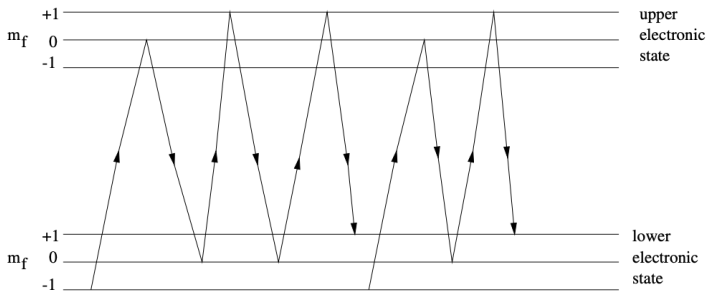


Figure 4: Energy transition schematic of magnetic substates in optical pumping process.

2.3 Breit-Rabi formula

The spin-$\frac{1}{2}$Hamiltonian for the hyperfine and Zeeman splitting is

$$H = -\mu_I \cdot (\mathbf{B}_J + \mathbf{B}_{ext}) - \mu_J \cdot \mathbf{B}_{est}$$

where μ_I is the nuclear magnetic moment, μ_I is the electronic magnetic moment, $\mathbf{B}_J$ the magnetic field at the nucleus arising from the rest of the atom, and $\mathbf{B}_{est}$ is the external magnetic field. The analytic solution to the Hamiltonian for the low-field case is the Breit-Rabi Formula derived in the prelab as follows,

$$\frac{\nu}{B_{ext}} = \frac{2.799}{2I+1}\text{MHZ/Gauss}$$

From this we can obtain the internal nuclear spin I of the Rubidium isotopes and using I allows us to find the Lande g factors.

2.4 Magnetic field with Helmholtz Coil

Helmholtz coil uses a pair of identical circular coaxial coils separated by a distance equal to their radius, a, carrying a current, i, and used to generate a magnetic field. In this experiment setup, a set of Helmholtz coil surrounds the Rubidium vapor bulb such that a magnetic field along the z direction is found in the center of the coils. Using the Biot-Savart Law, we can determine the magnitude of the applied magnetic field. Below, we substituted the $r^2 = z^2 + a^2$.

$$\begin{aligned} B &= \frac{2\mu_0 i}{4\pi} \int \frac{dl \times \hat{r}}{r^2} \\ &= \frac{2\mu_0 i}{4\pi} \int \frac{dl \sin\theta \hat{z}}{z^2 + a^2} \\ &= \frac{2\mu_0 i a}{4\pi (z^2 + a^2)^{3/2}} \int dl \hat{z} \\ &= \frac{\mu_0 i a^2}{(z^2 + a^2)^{3/2}} \hat{z} \end{aligned}$$

In the center of the bulb, we have $z = a/2$, $\mu_0 = 4\pi \times 10^{-7}$Wb/(Am), and N turns of the coil, B simplifies to

$$B = 0.9 \times 10^{-6} \frac{N \cdot i}{a} \text{ Tesla} \cdot \text{ m/A}$$

We require that the Helmholtz coil be place in the center for the field to be uniform both laterally and longitudinally. Longitudinally, the magnetic field is a superposition of the two coils field which both depends on a linear current. Laterally, the superposition is cosine of the central axis and the field has a second order approximation to be linear to the current.

3 Apparatus and Setup

The experimental setup can be seen in figure 5. In the center of the setup is the insulated container holding the rubidium vapor bulb, heater, temperature sensor, and photodiode. The heater is used to heat the vapor to a resonant temperature. A Rubidium light source emits light that has been circularly polarized into the cell. The photodiode is the detector for our measurements and reads out into an amplifier then to the oscilloscope. We wrap a Helmholtz coil (radius of 0.235 meters and 135 turns) around the cell to apply a magnetic field. An AC power supply that modulates

the magnetic field. Another set of coils is place perpendicular to the magnetic field coils to allow us to modulate the RF frequency. For this experiment, we will vary the magnetic field and the RF frequency so observe their behavior with Rubidium together.

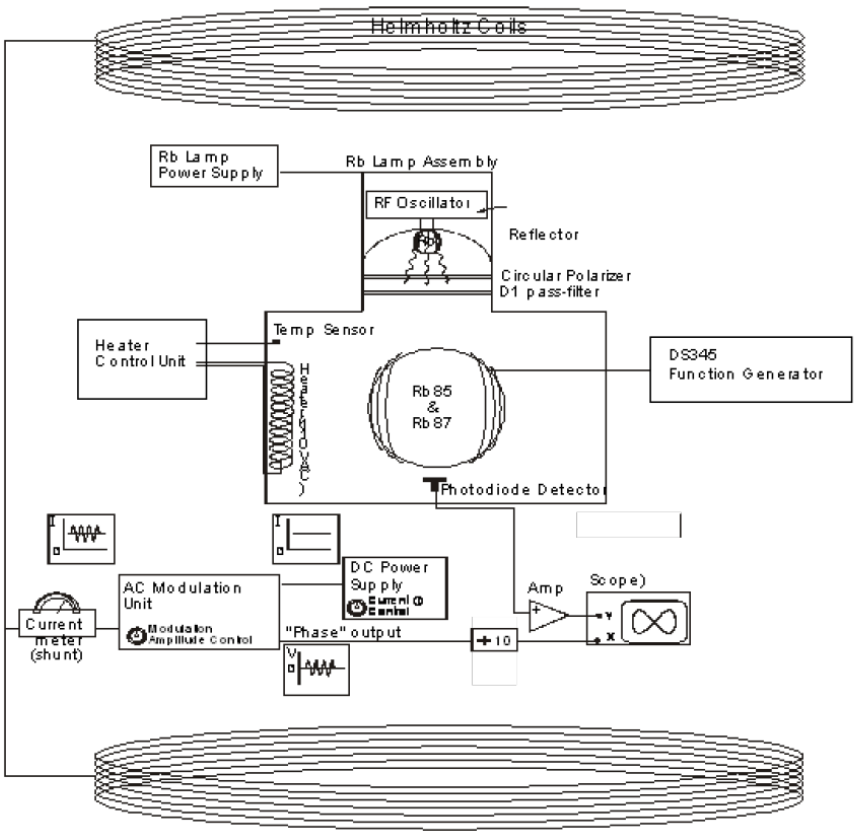


Figure 5: Block diagram of Equipment

4 Procedure

4.1 The Effect of Temperature on Signal Strength

Temperature has an important afffect in nuclear structure and optical pumping. By heating the glass cell, more rubidium atoms will be released, creating a higher vapor density that will attenuate the Rb lamp, and so attenuating the signal.

We observe the temperature effect by heating up the system to 48°C, then turning the haeter off and letting it cool down to between 38°C and 45°C. Based on the observations of the output signal, we observe that at optimal temperature (around 38°C for ^{85}Rb and 40°C for ^{87}Rb), the concentration of Rubidium was at its peak and so was the signal from the optical pumping. This dependence of Signal versus temperature largely follows the curve depicted in figure 6. This relationship between pumping intensity and temperature is likely because Rubidium is at resonance at a particular temperature. The temperatures for ^{85}Rb and ^{87}Rb differ because they have different resonance frequencies.

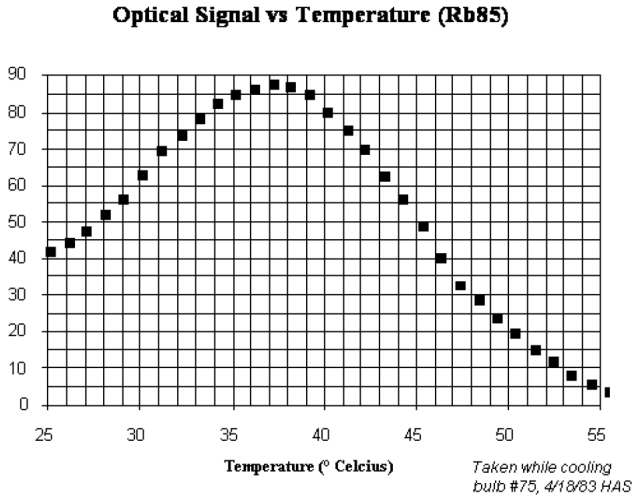


Figure 6: Optical signal amplitude vs. Temperature of Rubidium 85

4.2 RF Modulation

To detect optical pumping, we can repeat the process of allowing the atoms to "relax", and then observing the transient in absorption between the excitation and

relaxation of the atoms. In this experiment, we will be using two methods to find the resonance of Rubidium. The first method is to use the oscilloscope to modulate the RF frequency that then sweeps over the range of expected resonant frequencies (found from the Breit-Rabi formula) to induce emission. With a constant magnetic field, a 1.0 Amp current is passed through the Helmholtz coils, inducing Zeeman splitting. Using the DS345, signal generator to power the RF, the circuit diagram for this setup can be seen in figure 7.

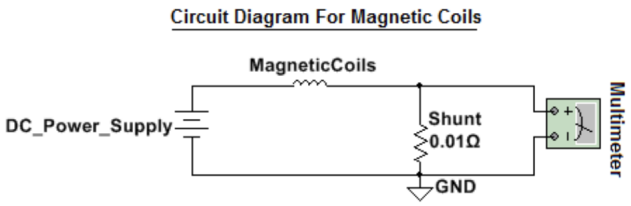


Figure 7: Circuit Diagram for Magnetic Coils

Lastly, the signal runs through he Pre-amp and then is outputting into the scope. Using the X-Y mode on the generator output and amplified photodetector output, we generated a sine wave signal of 10 Vpp centered at around 2200 Hz. Scanning over the range of frequencies, we find the resonant output to resemble two sharp peaks (figure 8) where ^{85}Rb is the highest peak, lower frequency (left) and ^{87}Rb is the smaller peak, higher frequency (right).

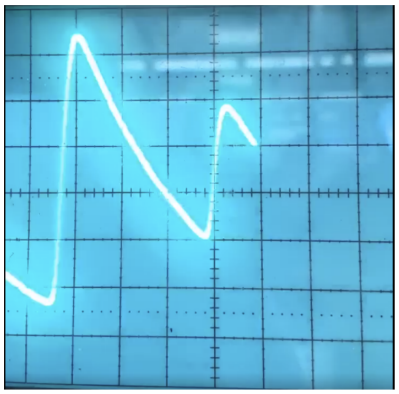


Figure 8: Amplified photodiode signal with RF frequency modulation

4.2.1 Magnetic field Modulation

The second method for finding the resonance of Rubidium is through modulation of the magnetic field. This method is quicker and more accurate because the RF modulation is more sensitive to noise and more difficult to determine the exact resonant frequency.

Connect the "Phase Out" signal from the coils to channel 1 and the amplified photo detector signal output to channel 2. In X-Y mode, you will see a sine wave figure but this is less helpful for determining the resonance, instead change the display on the oscilloscope to X-Y Dual Trace Mode. This changes the horizontal axis to be the magnetic field varying in time and the vertical axis to be the detector output varying back and forth. The effects of plotting these two sine waves in this manner displays a Lissajous figure (like a "figure eight") on the oscilloscope screen.

At resonance, the Lissajous figure will be perfectly symmetric otherwise it will be antisymmetric. An example oscilloscope display of the two Rubidium isotopes at resonance can be seen in figure 9. To collect data for the experiment, vary the current into coils (effectively varying the magnetic field) and adjust the settings until you find the resonant figure.

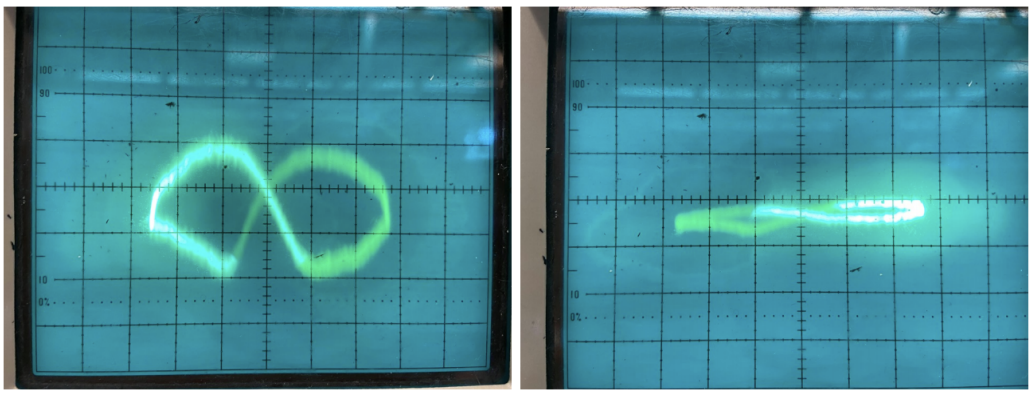


Figure 9: Magnetic field modulation resonance of ^{85}Rb (left) and ^{87}Rb (right)

5 Calculations and Data Analysis

5.1 Measurements and Fit

In this experiment, we recorded data of how the applied magnetic field varies with the resonant frequency of Rubidium vapor. By varying the current (effectively varying

the magnetic field), we can determine a linear relationship between the resonant frequency and the current applied. To mitigate systematic errors from measurement, we kept the temperature to be around 40°C which optimizes the intensity of the signal.

To perform the linear fit, we used a least squares regression method where

$$\chi^2 = \sum_{n=1}^{N} \left(\frac{y_i - f(x_i)}{\sigma_i}\right)^2$$

where y_i are the experimental resonant frequency outputs, σ_i are the errors, x_i is the input current, and our model function is the linear relationship $f(x_i) = mx_i + b$. Using the Python package, scipy.optimize.curve_fit, an example code snippet for the liner fit can be seen below.

```
def model(x, a, b):
    return a + b*x

def fit_linear(x, y):
    par, cov = fitter.curve_fit(model, x,y)
    errors = [np.sqrt(cov[0,0]), np.sqrt(cov[1,1])]

    a = par[0]
    ea = errors[0]
    print('x-intercept =\{0:6.2f\}+/-\{1:5.2f\} (Amps)'.format(a,ea))
    b = par[1]
    eb = errors[1]
    print('slope =\{0:6.2f\}+/-\{1:5.2f\} (MHz/Amps)'.format(b,eb))
    print('The best fit line is y =\{:.2f\} +\{:.2f\}x'.format(a, b))
    uncertainty_y = np.sqrt(ea**2 + eb**2)
    print('uncertainty of y =\{0:6.2f\} (MHz)'.format(uncertainty_y))
    print('\n')

    return par, errors, uncertainty_y
```

For each region and each isotope, the plots of the best fit line can be seen in figure 10 and the values of the slope and the intercept in table **??**. Furthermore, we can use this value to estimate the uncertainties of the best fit line, x-intercept, and slope from the method of least squares.[4]. The equations for m, b and their uncertainties are listed below

$$b = \frac{1}{\Delta}\sum_i x_i^2 \sum_i y_i - \sum_i x_i \sum_i y_i$$

$$m = \frac{1}{\Delta} N \sum_i x_i y_i - \sum_i x_i \sum_i y_i$$

where $\Delta = N\sum_i x_i^2 - (\sum_i x_i)^2$ and the estimated errors are

$$\sigma_b = \sigma\sqrt{\frac{1}{\Delta}\sum_i x_i^2}$$

$$\sigma_m = \sigma\sqrt{\frac{N}{\Delta}}$$

where the common error is $\sigma = \sqrt{\frac{1}{N-2}\sum_i (y_i - mx_i - c)^2}$

The best-fit line is not a good description of the data. We want to further perform a preliminary test of the quality of the fit from the best-fit straight line. We can determine this by plotting the residuals $R_i = y_i - y(x_i)$. If the data are consistent with a straight line, the residuals should have a mean of zero and show no obvious structure [4]. The plot of our residuals can be seen in figure 11. We can further find the sum of the residuals square $RSS = (\sum_i R_i)^2$ and determine the error of our predicted best fit line using the RSS and divide by $\sqrt{N-2}$ for two degrees of freedom assuming a Poisson distribution.

$$\sigma_y = \frac{(\sum_i R_i)^2}{\sqrt{N-2}}$$

In the last column, we also estimated the ^{2} value. This is useful for determining how well our fit performs by using $\chi^2 = \sum \frac{(O_i - E_i)^2}{\sigma_i^2}$ where O_i, E_i are the observed values and the expected values respectively and σ_i are the uncertainties. To estimate the probability that the straight line an adequate description of the observed data, we need to determine if the the χ square value cluster around the median value of χ^2_ν, where $\nu = N - r$, is the degree of freedom determined by subtracting the number of constraints r from the sample size N. Here, the quantile approximation of the χ^2 test is performed and accepted values between the upper tail and lower tails of the distribution is accepted. Accepted chi square values are between 3.940 (0.05, lower tail) and 18.307 (0.95, upper tail).

Source	x-intercept (Amps)	slope (MHz/Amps)	best fit line	Uncertainty (MHz)	χ^2	$(\sum R_i)^2$
Rb 85 negative	-0.21± 0.003	2.05± 0.004	y =-0.21 +2.05x	0.005	2.63	0.00026
Rb 85 positive	-0.17±,0.005	2.06± 0.006	y =-0.17 +2.06x	0.008	6.51	0.00065
Rb 87 negative	-0.32± 0.009	3.08± 0.01	y =-0.32 +3.08x	0.013	14.3	0.00143
Rb 87 positive	-0.25± 0.009	3.08± 0.01	y =-0.25 +3.08x	0.013	14.2	0.00142

From the table, our estimated errors are relatively small and the sum of residuals is relatively small indicating a good fit to the best fit line. Furthermore the χ^2 values are in the acceptable quantiles. This shows that our data collection process had small enough error such that we can use these values for the calculations in this experiment.

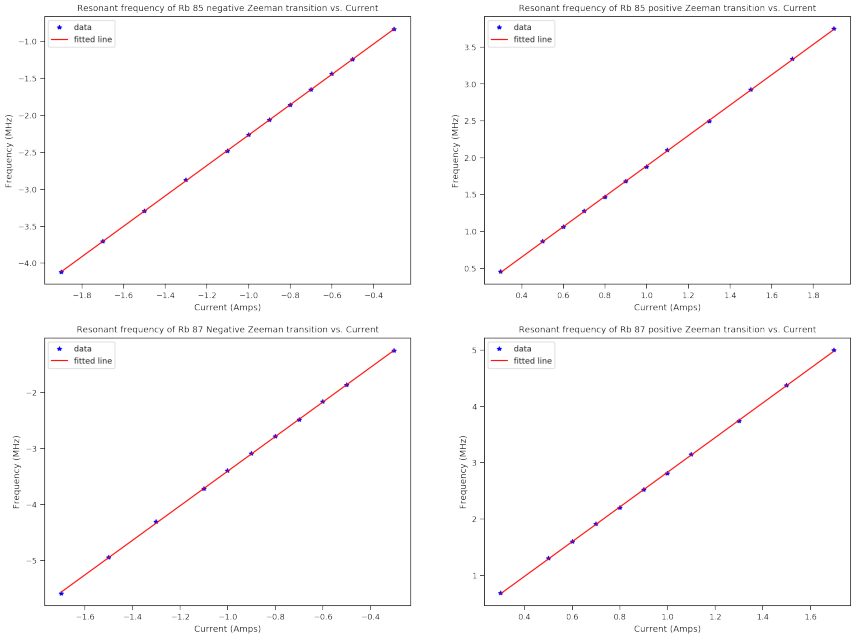


Figure 10: Best fit lines for positive and negative currents of Rubidium 85 and 87.

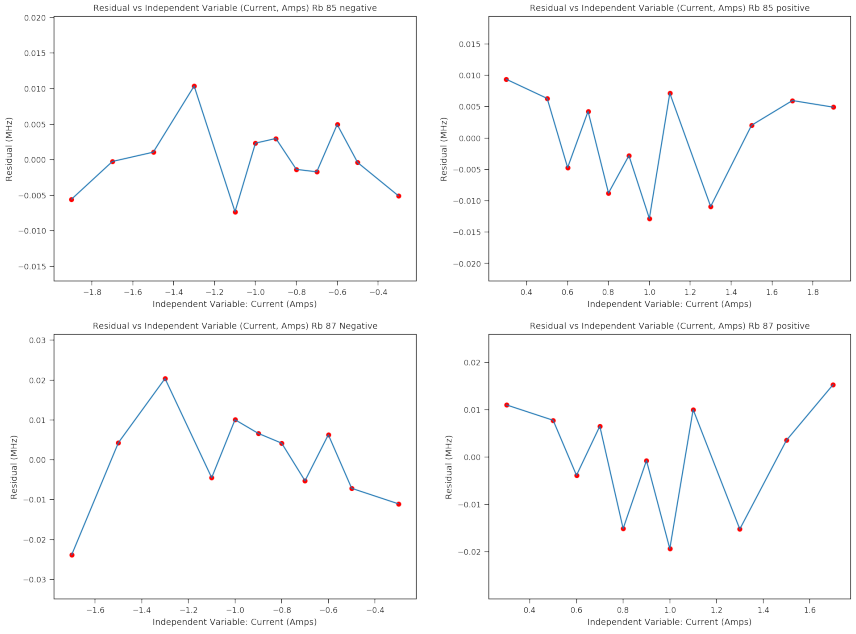


Figure 11: Residuals of best fitted lines

5.2 Calculations

Using the measurements taken of Rubidium at resonance, the Breit-Rabi equation, and the strength of the magnetic field at the bulb, we can solve for the nuclear spin states of ^{85}Rb (spin $I = 5/2 = 2.5$) and ^{87}Rb (spin $I = 3/2 = 1.5$) and the Earth's magnetic field. Then the nuclear spin equation is

$$I = \frac{1}{2}(\frac{0.025191 \times N}{a}\frac{i}{\nu} - 1)$$

Where the number of turns $N = 135$, the radius of the turns $a = 0.275 \pm 0.001$ (error on radius is based on the precision of a meter stick), the current i, and lastly ν is the frequency. Notice that in the formula above, there is a dependence on the inverse of the slope i/ν. We will be using the slope calculated from the linear fit. The uncertainty of the nuclear spin can be derived using error propagation using the previously estimated errors.

$$\frac{\sigma_I}{I} = \frac{0.0025191N}{2}\sqrt{(\frac{\sigma_a}{a})^2 + (\frac{\sigma_{1/m}}{(1/m)})^2}$$

Furthermore, we can determine the strength of the Earth's magnetic field by solving for the equation when the applied current is at zero. In other words, we will be using the y-intercept b as the zero field resonance to measure the local field. Notice that in table 1, the calculated magnetic field is smaller when the current is passing through the coil in the negative direction. This is likely because there is some geometric effect from the Helmholtz coil field that cancels out part of the Earth's magnetic field.

$$B_{earth} = \nu(2I + 1)/2.799 = b(2I + 1)/2.799$$

$$\frac{\sigma_B}{B_{earth}} = \frac{2I}{2.799}\frac{\sigma_b}{1/b}$$

Table 1 encapsulates the calculations discussed above for the Nuclear spin and Earth's magnetic field.

5.3 Magnetic Field at the Bulb

We can also calculated the magnetic field of the Helmholtz coils using the geometry and the current passed through them or by using the formula that incorporates the nuclear spin. Where

Isotope	Expected Nuclear Spin	Calculated Nuclear Spin	Calculated Earth's Magnetic Field
^{85}Rb negative	2.5	2.516 ± 0.002	0.45 ± 0.01
^{85}Rb positive	2.5	2.501 ± 0.002	0.37 ± 0.02
^{87}Rb negative	1.5	1.507 ± 0.001	0.46± 0.01
^{87}Rb positive	1.5	1.508± 0.001	0.36 ± 0.01

Table 1: Calculated values of nuclear spins of ^{85}Rb and ^{87}Rb and the Earth's magnetic field

Isotope	Resonant Frequency (MHz)	B (Gauss)
^{85}Rb negative	1.876 ± 0.005	4.02 ± 0.01
^{85}Rb positive	2.266 ± 0.005	-4.86 ± 0.01
^{87}Rb negative	2.811 ± 0.005	4.02 ± 0.07
^{87}Rb positive	3.394 ± 0.005	-4.850 ± 0.007

Table 2: Calculated field of coils using the resonant frequency of Rubidium

$$B = 0.9 \times 10^{-2} \times 135\frac{i}{a}$$

$$B = \frac{\nu(2I+1)}{2.799}$$

Each method has their own levels of precision. The first method uses the current and radius with uncertainties ±0.005 Amps and ±0.001 meters. Using a current of $1.00 \pm 0.005 Amps$, our expected field is $B = 4.42 \pm 0.024$ Gauss. The later method uses the errors of the resonant frequencies and nuclear spins. Tables 2 shows the calculated field values.

5.4 Pumping and Relaxation Times

We can further determine the pumping and relaxation times of the Rubidium isotopes at resonance. Using a current of 1.0 Amps, a square wave modulated signal at 1 Hz, and setting the scope display to X-Y mode, located the resonant signal. When the Rubidium vapor becomes more transparent (increase in density), the pumping is taking place and the signal intensity increases. During the relaxation position, the signal intensity decreases.

Because of the limitations of the instrument, it is very difficult to measure the pumping and relaxation time. We gave the best estimation we can by performing a slow motion recording of the signal and analyzing how long the pumping and relaxation time is from the signal.

The measured pumping time of ^{85}Rb is about 10 seconds and relaxation time is about 0.05 seconds. The measured pumping time of ^{87}Rb is about 14 seconds and relaxation time is about 0.03 seconds.

We expect the relaxation time to be a lot shorter than the pumping time because the pumping process requires more energy transitions of the isotopes while the relaxation time is a spontaneous event. We also expect the pumping time of ^{87}Rb to take longer than ^{85}Rb because it has more energy pumping levels. Since the resonant frequency of ^{87}Rb is higher than of ^{85}Rb, we also expect it to have a short relaxation time than ^{85}Rb.

5.5 Other Observations

We also looked at other phenomena of the Optical Pumping experiment. The signal has a nontrivial relation to temperature which affects the strength of the signal as mentioned earlier. Furthermore, we noticed that using the RF modulation technique, a low span allows us to see the peaks better. And at 2.18M Hz the peaks are about the same height. If we increase the frequency, we will see the second peak (Rb 87) amplitude increase because RB 87 has a higher resonant frequency. While using the field modulation method, a low field modulation is more sensitive to searching for the resonant frequency and is desired to provide higher precision. Additionally, when Helmholtz coils current is very small then we found a temperature independent zero field resonance. This happens because when there is no applied magnetic field, the Zeeman effect disappears. The local field (Earth field) is weak enough such that the energy splittings does not diverge.

6 Conclusions

In this experiment, we studied the effects and usages of Optical pumping. We studied quantum effects of the nuclear structure and behavior of Rubidium isotopes during Zeeman splitting. Using the techniques of optical pumping, we were able to determine the nuclear spins of each Rubidium isotope and from there calculate the Earth's magnetic field. This experiment displayed the powerful usage of optical pumping and allowed us to better understand the nuclear structure of atoms.

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Raw Data

Due to limited upload size on bcourses, please contact me for the raw data and python code used.

Current (A) Frequency (MHz) Frequency (MHz) Temperature Celsius

0.3 0.456 0.688 0.5 0.865 1.3 41 0.6 1.06 1.596 39.2 0.7 1.275 1.914 41.4 0.8 1.468 2.2 0.9 1.68 2.522 38.8 1 1.876 2.811 1.1 2.102 3.148 42.7 1. took this picture at 85 1.3 2.496 3.738 39.3 3. took picture at 85 1.5 2.921 4.372 42.3 1.7 3.337 4.999 43 1.9 3.748 distorted Distortions are because of the scope. Distortions dont appear when using the scope in the left station

-0.3 0.836 1.256 -0.5 1.242 1.869 -0.6 1.442 2.164 -0.7 1.654 2.484 39.9 -0.8 1.859 2.783 -0.9 2.06 3.089 38.4 -1 2.266 3.394 -1.1 2.481 3.717 40.6 2.. took this picture at 87 -1.3 2.874 4.309 38.1 -1.5 3.294 4.942 38.8 -1.7 3.706 5.587 ¡- 87 distort -1.9 4.122 distorted