

OPT - Optical Pumping

Signature Sheet

Student's Name Brandon Tran Partner's Name Lok Ching Lui

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 ^{85}Rb and ^{87}Rb . Draw qualitative energy-level diagrams for ^{85}Rb and ^{87}Rb 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

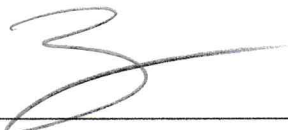
2019-04-26

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 at least one rubidium isotope, and have made an estimate of the earth's magnetic field. Show them to an instructor and ask for a signature.

Staff Signature



Date


4/30

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

Checkpoint Signatures

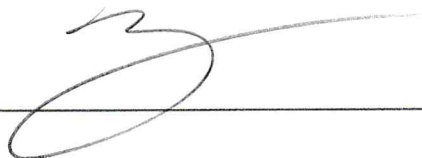
1. DS345 Preparation

Staff Signature

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2. Resonance Conditions and Symmetry

Staff Signature

A handwritten signature in black ink, consisting of a large loop and a trailing flourish, written over a horizontal line.

3. Error Analysis Methods

Staff Signature

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Optical Pumping of Rubidium Vapor

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(Dated: 4 May 2019)

In this experiment, ^{85}Rb and ^{87}Rb atoms were optically pumped to higher energy levels. Incorporating the Zeeman effect using a modulating magnetic field and a radiofrequency (RF) field, these atoms were continuously pumped and "de-pumped." Measurements of the resonance frequency and magnetic field values allowed a calculation of the Zeeman energy levels of these atoms. Using the Breit-Rabi equation, the nuclear spins of ^{87}Rb and ^{85}Rb were determined to be 1.520 ± 0.017 and 2.542 ± 0.032 , respectively. The magnitude of Earth's magnetic field at the location of Berkeley's Physics 111 Laboratory was also calculated to be $0.314 \text{ Gauss} \pm 0.029 \text{ Gauss}$ from the data.

Keywords: rubidium gas, optical pumping, Zeeman levels, nuclear spin, field modulation

I. INTRODUCTION

Optical pumping is a process in which light is used to raise or "pump" electrons in an atom from a lower energy level to a higher one. In this specific experiment, circularly polarized light was used in conjunction with the Zeeman effect (in a weak magnetic field), to move electrons in ^{85}Rb and ^{87}Rb atoms to their highest ground state Zeeman sublevel.

The technique of optical pumping was developed by Nobel Prize winner Alfred Kastler and is often used in the construction of lasers. where population inversion is achieved by pumping the active laser medium. Along with laser construction, optical pumping has many wide spread applications that include precise measurements of hyperfine level splittings in atoms and atomic clocks, measurements of weak magnetic fields, and MRI enhancement.¹

In this paper, calculations of the nuclear spins of ^{85}Rb and ^{87}Rb and the Earth's magnetic field will be obtained by a measurement of the resonant frequency and magnetic field values that match the Zeeman energy level splittings of the rubidium atoms. Section II describes the relevant atomic theory to understand optical pumping and how optical pumping works, section III and IV describes the setup and procedure in this experiment, and section V describes the results of our experiment.

II. BACKGROUND & THEORY

This section describes the energy structure of the rubidium atom. Along with a discussion of the Zeeman effect, a detailed explanation of how optical pumping works will be discussed. We assume the reader is familiar with the finer details of the atomic energy splittings associated with the fine and hyperfine levels.

A. Atomic Structure and Energy Levels

Electrons in atoms are bounded by potentials that give rise to quantized energy levels. Referring to Fig. 1 and Fig. 2, the principal energy state or hydrogenic state arises from the coulomb interaction between the positively charged nucleus and the negatively-charged electrons.

However, due to relativistic corrections and the spin-orbit coupling of electrons, these hydrogenic states split further, giving rise to the fine structure or electron spin-orbit structure. Because the electron has spin, the total angular momentum of the electron can be described by its orbital angular momentum l and its spin number s . In vector notation, the total angular momentum \mathbf{J} of the electron is

$$\mathbf{J} = \mathbf{L} + \mathbf{S} \quad (1)$$

where \mathbf{S} is the spin of the electron and \mathbf{L} is the orbital angular momentum of the electron. The fine structure splits the gross structure into states with $L - S \leq J \leq L + S$.

A further splitting arises due to the interaction between the nuclear magnetic dipole moment and the magnetic moment of the electrons. This splitting causes the hyperfine structure or the electron/nuclear spin structure. Because the nucleus has a spin \mathbf{I} associated with it, the total angular momentum of the atom \mathbf{F} is then defined as

$$\mathbf{F} = \mathbf{J} + \mathbf{I} \quad (2)$$

The hyperfine structure splits the fine structure into states with $I - J \leq F \leq I + J$.

The rubidium atom, whose electron configuration is

$$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s \quad (3)$$

has only one valence electron in the $5s$ state. Because all of the other electrons are tightly bounded, this experiment will focus on this lone "optically active" valence electron.

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Referring to Fig. 1 and Fig. 2 for the rubidium atom, another splitting occurs to the hyperfine levels when atoms are present in a weak external magnetic field, \mathbf{B}_{ext} . This is called the Zeeman effect and gives rise to the Zeeman splittings.

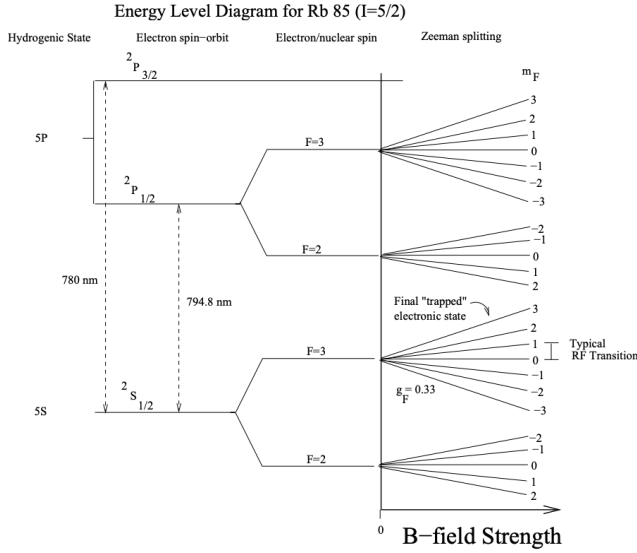


FIG. 1. Energy levels and splittings in ^{85}Rb .

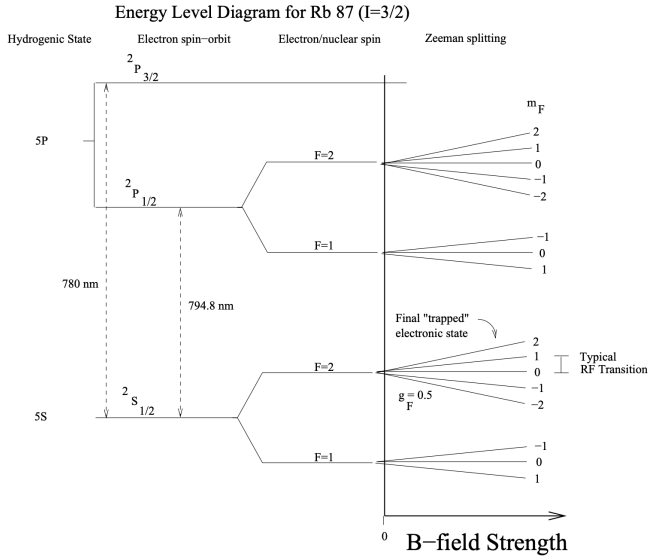


FIG. 2. Energy levels and splittings in ^{87}Rb .

For a given F , the Zeeman effect causes the hyperfine levels to split into $2F+1$ levels with the m_F values ranging from $-F \leq m_F \leq F$. The energy of these Zeeman levels is given by

$$E = E_0 + g_F m_F \mu_B B_{\text{ext}} \quad (4)$$

where E_0 is the energy of the eigenstate when \mathbf{B}_{ext} is zero, μ_B is the Bohr magneton, and g_F is the Landé g -factor, defined as

$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} \quad (5)$$

and

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad (6)$$

The energy difference between adjacent Zeeman levels for a given F is then given by

$$\Delta E_{\text{Zeeman}} = g_F \mu_B B_{\text{ext}} \quad (7)$$

Now, in this experiment, we will only focus on the Zeeman splittings in the highest F ground state of rubidium. For the ground state of rubidium $s=\frac{1}{2}$ and $l=0$, so $j=\frac{1}{2}$. Noting that ΔE_{Zeeman} is just $h\nu$ and $F=I+J$, Eq. 7 can be rewritten as

$$\frac{\nu}{B_{\text{ext}}} = \frac{2.799}{2I+1} \text{MHz/gauss} \quad (8)$$

which is known as the Breit-Rabi equation.

B. Optical Pumping

Consider Fig. 2 of the ^{87}Rb structure and the effect of shining left-circularly polarized light on ^{87}Rb vapour with Zeeman splitting in a weak magnetic field. Focusing on the ground state $^2S_{1/2}$ and the first excited state $^2P_{1/2}$ levels, when resonant optical light is incident on the rubidium vapour and is absorbed, the electron in the ground state $^2S_{1/2}$ will make a transition into the $^2P_{1/2}$ level. Since the light is circularly polarized (carrying one unit of angular momentum) and if we shine in the direction of the external magnetic field, however, then the absorption of the photon must mean that $\Delta m_f = +1$. So an electron in $F=1$ and $m_f = -1$ ground state can only transition to a substate with $m_f = 0$ in the excited state.²

When this electron falls back down to its ground state due to spontaneous emission, however, dipole radiation rules allow for $\Delta m_f = 0, \pm 1$ with equal probability, meaning it has a $\frac{2}{3}$ chance of having a higher m_f value than it was before when it was in the ground state. The atom will absorb and reradiate again, and if nothing happens to disturb the Zeeman levels during this process, all the atoms will be "pumped" into the $F=2$ and $m_f = 2$ state after multiple absorptions and emissions. Moreover, when the atom reaches this level, it can no longer absorb the resonant photons because there does not exist

a state with $m_f = 3$ in this example and conservation of momentum dictates $\Delta m_f = +1$ upon absorption. Referring to Fig. 1 and Fig. 2, the final pumped states of ^{85}Rb and ^{87}Rb are the $F=3, m_f = 3$ and $F=2, m_f = 2$ levels of the $^2S_{1/2}$ state, respectively. This technique of raising the energy levels of the atom is called optical pumping.

When pumping is achieved, the rubidium vapour becomes transparent to the polarized light as it can no longer absorb any more. By introducing a radiofrequency (RF) radiation with the energy equal to the Zeeman splitting energy, $\Delta E_{\text{Zeeman}} = h\nu$, where ν is the frequency of the light, the saturated pumped levels can be "depumped" into lower Zeeman levels to allow pumping to occur again.

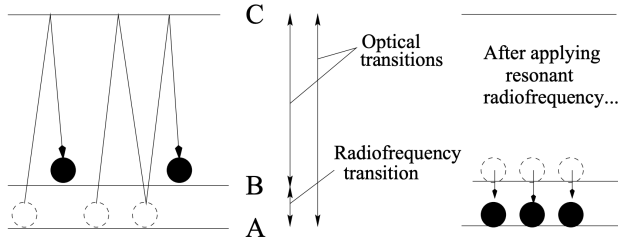


FIG. 3. Simple illustration of optical pumping. Adapted from [3].

Fig. 3 illustrates this process of pumping and depumping. Atoms in the ground state A can be pumped into the state B through continuous iterations of absorbing and emitting optical radiation. When all the atoms end up in state B, pumping can no longer occur. But by applying a resonant RF field equal to the Zeeman splitting, transitions from B to A can be induced, and pumping can occur again. Looking back at Eq. 8, the Breit-Rabi equation, one can see that the resonant RF frequency depends linearly on the strength of the externally applied magnetic field. By measuring the resonant frequencies at various externally applied magnetic fields or vice versa, one can determine the nuclear spins of the rubidium atoms.

III. EXPERIMENTAL SETUP

The experimental setup is shown on Fig. 4 on the next page. The rubidium lamp provides the optical pumping light by traveling through a circular polarizer and a D1 filter. By applying this polarized light at the proper frequency using the D1 filter, transitions from the ground state to the excited states of the rubidium atoms can be induced. The light intensity from the rubidium lamp is detected by the photodiode. When all the atoms are pumped, we see an increase in light intensity detected as no more photons can be absorbed. By introducing a radiofrequency signal of the right frequency to stimulate transitions to lower Zeeman levels, a decrease in signal

intensity will be detected in the photodiode as the system is being pumped again.

A. Helmholtz Coils

The Helmholtz coils provide the weak magnetic field needed to provide Zeeman splitting to the atoms. It is powered by a DC power supply and can also be modulated using an AC modulation unit. The number of turns of the coils is $N=135$ and its radius is $R=27.5$ cm. The strength of this magnetic field, which determines the strength of the resonant RF frequency, can be determined by considering the magnetic field at a distance z from the center of a loop of current. Recall the formula is

$$\mathbf{B}_H(z) = \frac{\mu_0 i}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \hat{\mathbf{z}} \quad (9)$$

By placing two loops at a distance $\pm \frac{R}{2}$ and using superposition, the magnetic field at the rubidium sample becomes

$$\mathbf{B}_H(0) = \frac{8\mu_0 i}{5\sqrt{5}R} \hat{\mathbf{z}} \quad (10)$$

Using $\mu_0 = 4\pi \times 10^{-7}$ and N coils, we then have the magnetic field of the Helmholtz coils is then

$$B_H = 0.9 \times 10^{-6} \cdot \frac{Ni}{R} \text{ Tesla} \quad (11)$$

Then we can determine the Helmholtz field by measuring the current i passing through it.

B. Rubidium Bulb or Cell

The rubidium bulb contains the ^{85}Rb and ^{87}Rb atoms and is vaporized using the heater control unit. The bulb contains a low density of rubidium atoms and is mixed with a buffer gas to minimize the mixing of states. To achieve pumping, the rubidium bulb must be heated by the control unit so that it remains in a vapor state.

As in Fig. 4, the radiofrequency signal is provided by the coils surrounding the rubidium lamp and the function generator connected to it. Without the RF field, the atoms will be all pumped eventually, and a maximum photodiode signal will be present. The RF provides a change in this photodiode signal by depumping the atoms into lower Zeeman levels so that pumping can occur again.

IV. PROCEDURE

Since the main goal of this experiment is to calculate the nuclear spins of the rubidium isotopes and Earth's

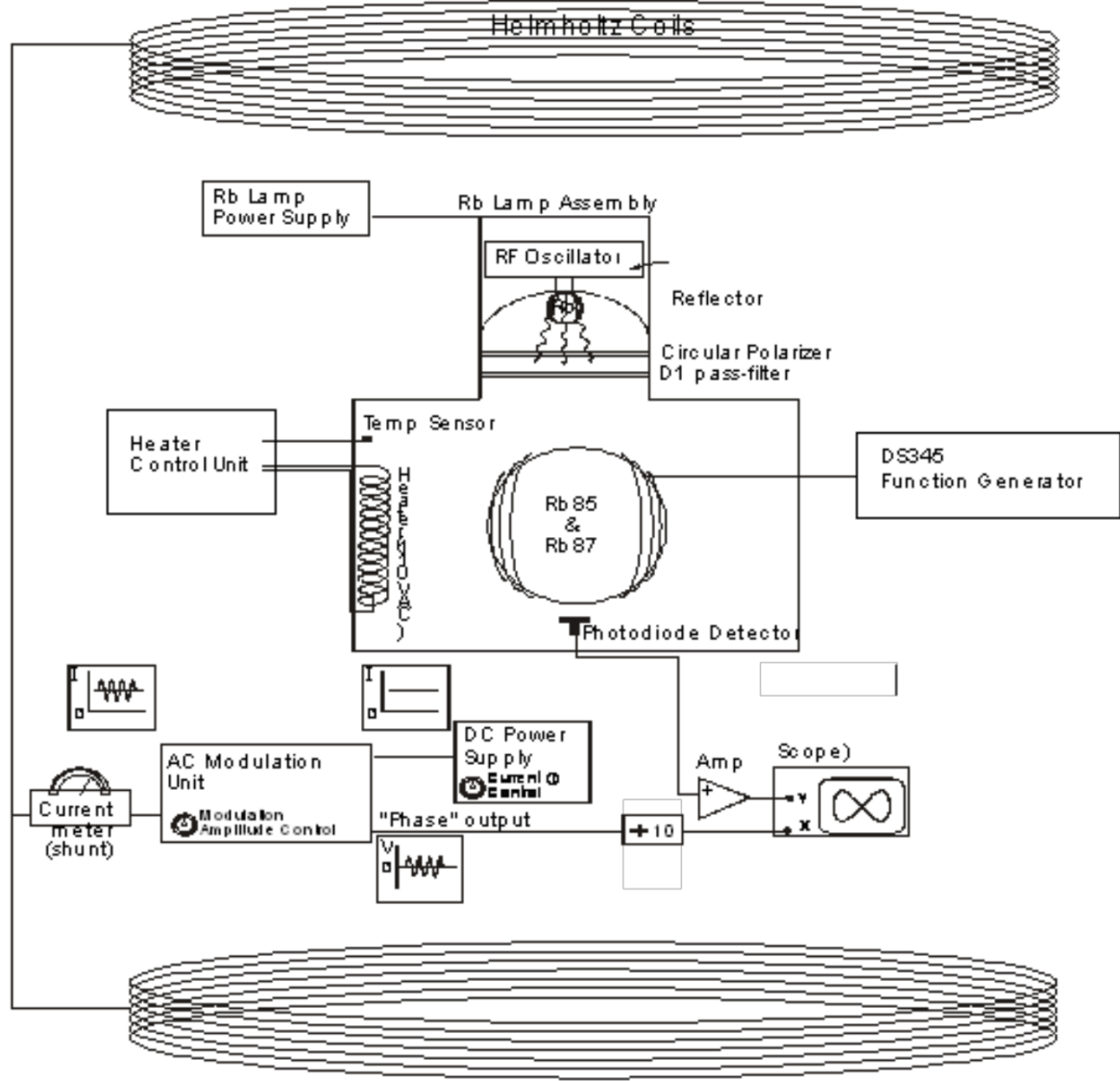


FIG. 4. Experimental setup for optical pumping. Adapted from [4].

magnetic field, a determination of the resonant RF frequency ν values and the associated external magnetic field \mathbf{B}_{ext} needs to be carried out to use in the Breit-Rabi equation. The resonant RF frequency can be determined in one of two ways: modulating the RF frequency or modulating the magnetic field.

A. RF Frequency Modulation

By sweeping through the values of the RF frequency for a given Helmholtz field, we can find the resonance frequency needed to induce stimulated emission in the rubidium vapor.

First, the sample is heated to a sufficient amount and

a 1A DC current is driven through the Helmholtz coil to start with. This induces Zeeman splittings in the rubidium atoms and the strength of this current determines the strength of the resonant RF frequency between the Zeeman levels. The RF frequency is driven using a DS345 function generator with a carrier wave centered at around approximately 2.8MHz with a ramp frequency modulation.

The signal from the photodiode is sent into a preamp and then CH2 of the oscilloscope and the function generator output is sent to CH1. As the resonant RF field depumps electrons into lower m_f levels, these depumped atoms can now be pumped, and the changes in opacity (indicated by a dip in the photodetector output) shows that the atoms are absorbing light and being pumped.

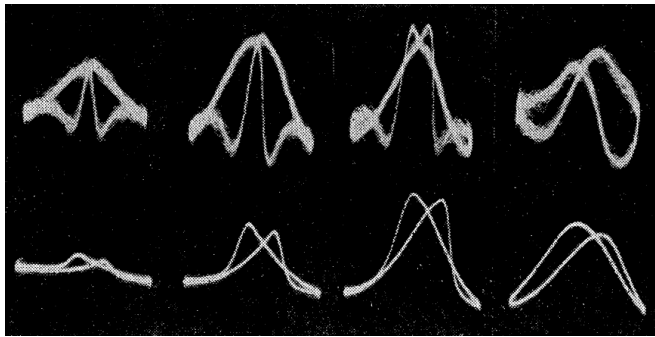


FIG. 5. Oscilloscope traces of Lissajous curves. Adapted from [5].

By changing the carrier RF frequency and the span, we can search for resonance on the oscilloscope by noting the opacity changes as a function of frequency. When resonance is found, a more accurate reading of the resonant frequency can be made by reducing the span of our modulated wave to "hone" in on the resonance. This process can be repeated by changing the DC current value powering the Helmholtz coils and finding the new resonance value by the method above.

Although this method works to find resonance, it is not as accurate as modulating the magnetic field. This is because RF frequency and the function generator can only be changed in discrete steps whereas the current driving the magnetic field can be changed continuously by a current knob.

B. Magnetic Field Modulation

Instead of the RF frequency modulation, the magnetic field provided by the Helmholtz coil can be modulated. This provides a quicker and more accurate way of finding the resonance frequency. Turning off the RF frequency modulation and driving the function generator powering the RF coils at a fixed frequency, we can search for resonance by a magnetic field modulation. Referring to Fig. 4, the AC modulation unit was turned on and was modulated at a value big enough to show the changes in opacity.

The phase out signal of the AC modulation unit is now connected to CH1 of the scope instead of the function generator's output and the scope was set to XY mode. We should observe what is known as a Lissajou curve on the scope as can be seen in Fig. 5.

By changing the current powering the Helmholtz coils, we can find resonance by noting that the Lissajous curve should be symmetric about the y-axis. This indicates that there is an equal change in transparency about the DC current value and thus this current matches the fixed resonance frequency of the splitting.

This Lissajous curve can be explained by a simple model in which the modulated magnetic field of the

Helmholtz coils is of the form $B_H = \sin(t)$ and at resonance the photodetector output should be of the form $\sin^2(t + \phi)$, where t is the time and ϕ is a phase shift that can be controlled on the coil driver panel.

By changing the value of the fixed RF frequency and searching for resonance by varying the current driving the modulating magnetic field, we can note at what magnetic field values gives the resonant frequency by noting the symmetry of the Lissajous curve. To obtain a more accurate measurement, the modulation amplitude can be adjusted even smaller to hone in on the resonance.

V. RESULTS AND ANALYSIS

This section contains the main results of this experiment. We first note how the signal intensity from the photodiode depends on the temperature of the rubidium isotopes. We then find a resonance signal at zero external magnetic field. Lastly, the nuclear spins of the rubidium isotopes and the Earth's magnetic field value will be determined.

A. Signal Intensity vs Temperature

For optical pumping to occur, the temperature of the rubidium atoms must be high enough so that it is in a vapor state, and it must also be low enough to not cause mixing of states.

Heating the rubidium atoms off the wall into the rubidium cell will cause a higher vapor density that attenuates the rubidium lamp more when it is not optically pumped. As a result, the detected signal (the difference in optical transmission in the cell in the presence and absence of pumping) will be larger. When the temperature is too high, however, and the vapor density increases even further, Rb-Rb collisions and other effects like mixing reduce the lifetime of the optically pumped state and so reduces the signal.

By locating the resonant frequency values of each isotope and examining the photodiode detector signal on the scope, we find that the maximum signal for ^{85}Rb occurs when the temperature is at 38°C and 41°C for ^{87}Rb .

B. Zero Field Resonance

With the RF field off and the magnetic field set in reverse polarity, we sweep the current driving the Helmholtz coils and find a resonance at a current of $0.1\text{A} \pm 0.02\text{A}$. This corresponds to a magnetic field of about $0.442\text{ Gauss} \pm 0.088\text{ Gauss}$. This current should not exist if the Helmholtz coils were perfectly aligned with the Earth's magnetic field, and this nonzero current value of zero resonance indicates there are other external magnetic fields besides the Helmholtz coils.

Zero field resonance occurs when the applied

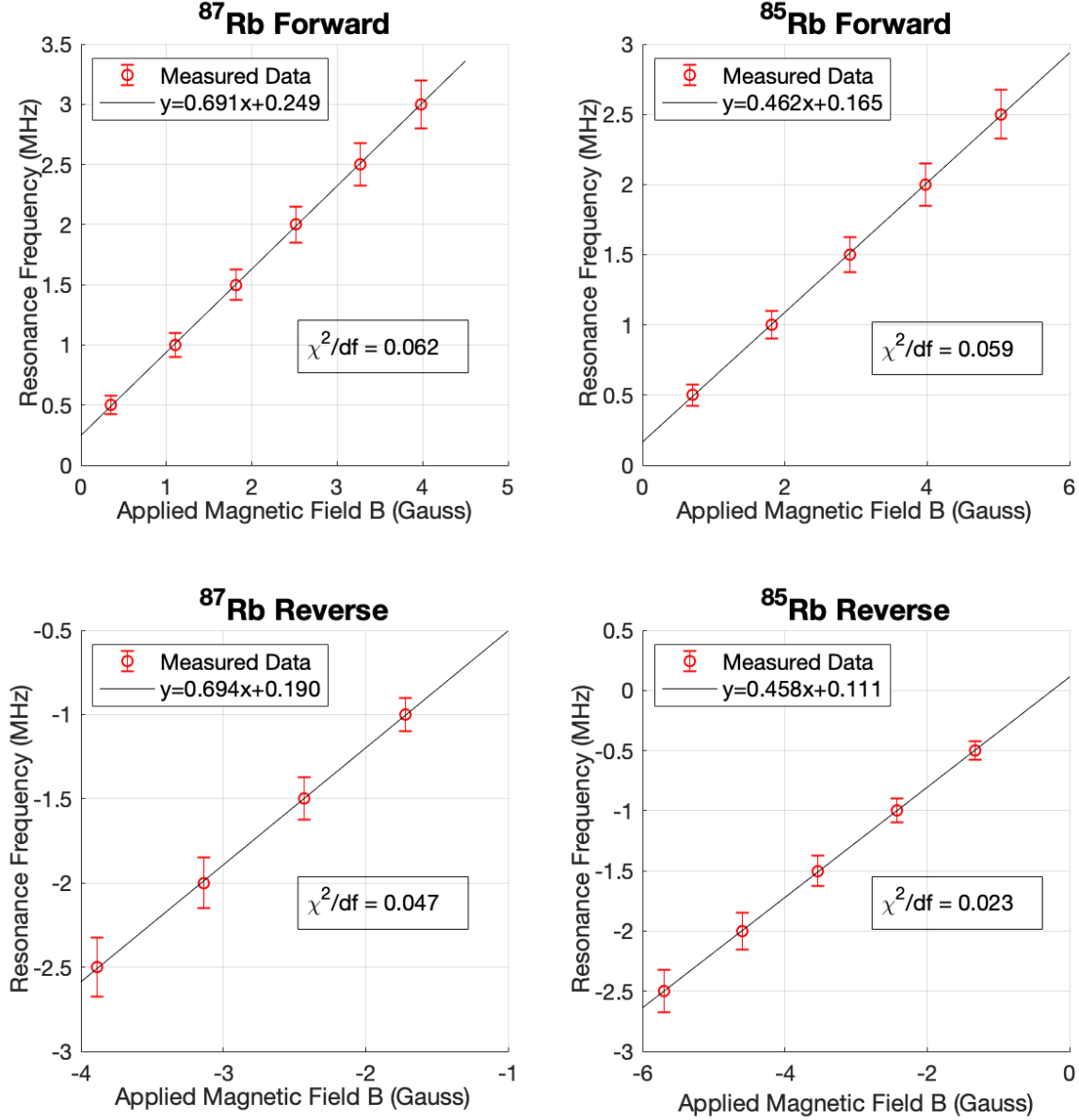


FIG. 6. Resonant RF frequencies as a function of the applied Helmholtz magnetic field B_H for ^{85}Rb and ^{87}Rb .

Helmholtz field cancels the Earth's magnetic field, leading to an overall zero net external magnetic field. The Zeeman levels become degenerate, and there is no longer a distinction between the Zeeman levels. There can no longer be pumping of the atoms and a distinct dip in the scope indicates more light is being absorbed by the vapor.

C. Determining the Nuclear Spins of ^{85}Rb and ^{87}Rb

By finding the resonant RF frequency and magnetic field values from the Helmholtz coils by using the procedure described in the magnetic field modulation subsection, the Breit-Rabi equation (Eq. 8) can then be used to find the nuclear spins of the rubidium isotopes. Fig. 6 shows the plots of resonant RF frequencies as a function of the Helmholtz field B_H for both ^{85}Rb and ^{87}Rb in forward and reverse magnetic field polarities (and allowing "negative" frequencies).

TABLE I. Nuclear Spin of ^{85}Rb and ^{87}Rb

| Isotope | Polarity | Slope (MHz/Gauss) | $I_{\text{calculated}}$ | I_{actual} |
|------------------|----------|-------------------|-------------------------|---------------------|
| ^{85}Rb | Forward | 0.462 ± 0.009 | 2.530 ± 0.054 | 2.5 |
| ^{85}Rb | Reverse | 0.458 ± 0.006 | 2.555 ± 0.036 | 2.5 |
| ^{87}Rb | Forward | 0.691 ± 0.009 | 1.525 ± 0.022 | 1.5 |
| ^{87}Rb | Reverse | 0.694 ± 0.012 | 1.516 ± 0.026 | 1.5 |

A least-squares fit was performed for each set of data with associated chi-squared values displayed in the figure. Errors tended to increase as the magnitude of the magnetic current increased. These errors were calculated by noting the range of magnetic field values that seem to produce resonance as seen by the symmetry of the Lissajou curve on the scope and propagated to the frequency errors by using the Breit-Rabi equation. Multiple measurements of the resonant frequency values and errors were also made at each magnetic field value for a better error calculation.

From the least-squares fit, the slope can be calculated and therefore the nuclear spins of the isotopes can be determined. The results of these calculations using the data from Fig. 6 can be seen in Table I.

From the slope calculations, the nuclear spins can be determined by noting from the Breit-Rabi equation that

$$\text{slope} = \frac{2.799}{2I + 1} \quad (12)$$

Calculating this for each of the four graphs and averaging the forward and reverse polarity values of each isotope in Table I, we determine that the nuclear spins of ^{85}Rb and ^{87}Rb are $I_{85} = 2.542 \pm 0.032$ and $I_{87} = 1.520 \pm 0.017$, respectively. Compared to the actual values of 2.5 and 1.5, these calculated values are within 2% of the actual values.

D. Calculation of Earth's Magnetic Field

To determine the magnitude of Earth's magnetic field, we combine the data from the forward and reverse polarity of each isotope into two graphs, one for ^{85}Rb and one for ^{87}Rb . These two new graphs are again fitted using the least-squares method.

Now there are two ways to calculate Earth's magnetic field, one is to see where the line crosses the x-axis and that is Earth's magnetic field value. The other way is to determine the y-intercept and noting that from the Breit-Rabi equation,

$$B_{\text{ext}} = B_H + B_{\text{Earth}} \quad (13)$$

Now the y-intercept is equal to

$$y - \text{intercept} = \frac{2.799}{2I + 1} \times B_{\text{earth}} \quad (14)$$

The results of these calculations can be seen in Table II. By calculating the y-intercept for each of the isotopes and taking an average, we find that the magnitude of Earth's magnetic field is $B_{\text{Earth}} = 0.314 \text{ Gauss} \pm 0.029 \text{ Gauss}$.

TABLE II. Earth's Magnetic Field B_{Earth}

| Isotope | y-intercept(MHz) | B_{Earth} (Gauss) |
|------------------|-------------------|----------------------------|
| ^{85}Rb | 0.146 ± 0.005 | 0.314 ± 0.010 |
| ^{87}Rb | 0.219 ± 0.005 | 0.314 ± 0.07 |

VI. CONCLUSION

Through the optical pumping of rubidium vapor, the nuclear spins of ^{85}Rb and one for ^{87}Rb were calculated to be 2.542 ± 0.032 and 1.520 ± 0.017 , respectively. These values are extremely accurate for an undergraduate laboratory. Earth's magnetic field was also determined to have a value of $0.314 \text{ Gauss} \pm 0.029 \text{ Gauss}$. The precision and ease of this experiment provides many practical applications from atomic clocks to MRI, and has provided great context for illustrating quantum mechanical concepts.

ACKNOWLEDGMENTS

We would like to thank the Physics 111B staff for their patience and guidance during this experiment. Without you, we would still be trying to figure out how to setup the experiment.

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⁵W.E. Bell, A.L. Bloom, "Optical Detection of Magnetic Resonance in Alkali Metal Vapor," Physical Review (1957).