# Optical Pumping in $^{85}$Rb and $^{87}$Rb

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(Dated: December 14, 2015)

Our experiment aimed to determine the g-factors for the isotopes of Rubidium 85 and 87 and determine the Rabi Flopping Oscillation frequency for $^{87}$Rb with varying voltages. Optical pumping was used to split the ground state F sublevels of Rubidium into the M sublevels through the Zeeman Effect. The g-factors of each isotope was determined to be.... The Rabi Flopping Oscillation was determined to be 3.5 ± .3 ms at 5V, 4.4 ± .3 ms at 7V, and 10.7 ± .3 ms at 10V.

## I. INTRODUCTION

Optical pumping is a powerful method for exploring the atomic structures of $^{85}$Rb and $^{87}$Rb. This experiment is capable of observing the Zeeman splitting of Rubidium isotopes using radio frequency and magnetic fields. This allows for energy level transitions of the electrons in the ground state. In 1966, Alfred Kastler was awarded the Nobel Prize in Physics for his work in the discovery and development of optical pumping [1]. His work helped to better understand the nuclear magnetic moment associated with the atom.

Rubidium is an ideal atom for optical pumping it has only one valence electron. This makes it a hydrogenic atom. In exploring the Zeeman effect, we will be analyzing the transitions from $^2S_{1/2}$ to $^2P_{1/2}$.

This paper explores a myriad of questions governed by quantum mechanics. First, we will explore atomic structure and the equations describing their behavior. Section II is dedicated to explaining spin, angular momentum, and nuclear magnetic moment in the perspective of quantum mechanics. Next, this paper will investigate how these ideas pertain to optical pumping and the Zeeman effect, also explained in Section II. Lastly, Section II will introduce the ideas of the Lande g-factor, as well as how one may calculate it. Section III explains the experimental set up, including the purpose of certain arrangements. Section IV will discuss the analysis of our results and the calculation of the angular momentum I and the Lande g-factor and the Rabi Flopping Oscillation time periods of 87Rb. Section V will be a final discussion of our experiment including error analysis.

## II. THEORY

### A. Hyperfine Structure

Hyperfine structures are splittings in the atomic spectra due to interactions within the nucleus. Different quantum factors are responsible for these splittings such as magnetic dipole moment and nuclear angular momentum. By obtaining experimental data regarding the hyperfine structures, the experimentalist is able to solve the quantum numbers for nuclear magnetic moment and nuclear spin angular momentum. Because these splittings are governed by nuclear interactions, the energy gaps for the splits may be minuscule.

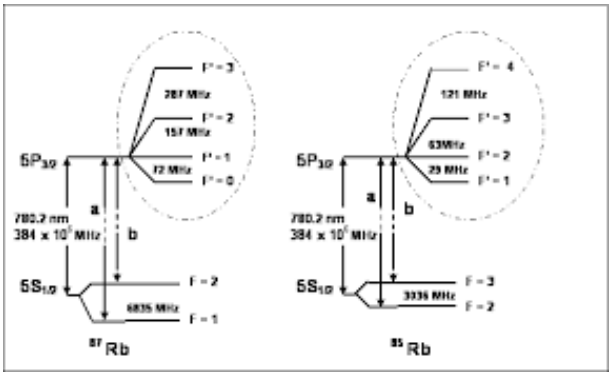



Figure 1. Atomic energy level diagram for $^{85}$Rb and $^{87}$Rb. Within this diagram is the hyperfine splitting of Rubidium. As illustrated, many of the gaps occur with a low frequency gap. This means that there would be a very high resolution associated with acquiring these dips.

Determining the good quantum numbers in optical pumping becomes difficult in the presence of a magnetic field. During the experiment, there are times where the magnetic dipole quantum numbers are correct and times where the angular momentum quantum numbers are correct. The quality of the quantum numbers are dictated by the energy levels in relation to B in each Zeeman region. There is a transition during the experiment which is further explained in the upcoming sections. The perturbing Hamiltonian for the hyperfine structure is written

$$H_{hf} = A\vec{I} \cdot \vec{J}, \tag{1}$$

where I is the nuclear spin angular momentum and J is the total electronic angular momentum. J is determined by

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

where $\vec{L}$ is orbital angular momentum and S is the spin. In the coupling of perturbing Hamiltonian, neither $m_I$ nor $m_J$ are good quantum numbers (the magnetic mo-

ment). In this situation, the good quantum numbers become

$$F = \vec{I} + \vec{J}, \tag{3}$$

where F is the total angular momentum. The nuclear spin angular momentum for $^{85}$Rb is 3/2 and 5/2 for $^{87}$Rb. The F values are illustrated in Figure 1 for each isotope. The allowed F transitions are ± 1. The degeneracy is 2F+1.

### B. Zeeman Effect

For alkali metals in the presence of an external magnetic field, more splittings occur due to the Zeeman effect. The Zeeman splittings occur at smaller energy gaps than the hyperfine splittings due to a weak magnetic field. The Hamiltonian for the Zeeman splitting is written

$$H = A\vec{I} \cdot \vec{J} - \frac{\mu_I}{J} J \cdot B - \frac{\mu_J}{I} I \cdot B, \tag{4}$$

where $\mu_I$ is the nuclear magnetic moment and $\mu_J$ is the total electronic dipole moment. The same degeneracy of 2F+1 occurs for the Zeeman splitting. For the sake of simplicity, the last term may be ignored due to it's significantly smaller value. Thus, the equation can then be written

$$H = A\vec{I} \cdot \vec{J} - \frac{\mu_I}{J} J \cdot B, \tag{5}$$

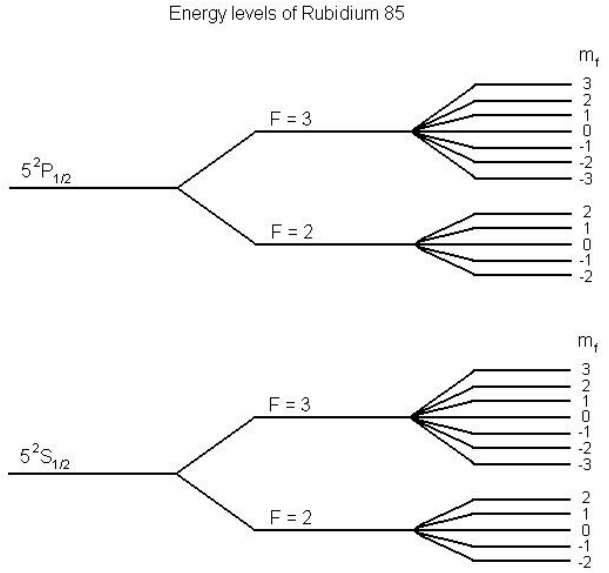



Figure 2: An illustration of the Hyperfine splitting with the Zeeman splitting shown between each energy level gap. Energy gaps for the Zeeman splitting are clearly much smaller than the hfs. This requires a significantly higher resolution. The energy transitions that will be explored are between $^2S_{1/2}$ to $^2P_{1/2}$. $^2P_{3/2}$ will be ignored.

In working with magnetic fields, the experimentalist must consider other external magnetic fields that may influence his/her experiment. The Earth's magnetic field plays a role in the total magnetic field of the system for optical pumping. The Zero Field Transition is a large dip where the horizontal magnetic field has a net force of zero by the instrument canceling out perfectly with the Earth's magnetic field. The electrons are absorbed at the greatest rate during the zero field transition. All of the electrons are at the ground state in this position before absorbing the photons provided by the RF discharge lamp. Outside of this dip, there is a flat line because there is no absorption at these points. The zero field transition dip is a very thin dip where all the absorption takes place at one select location.

The second Zeeman splitting that is observed is the quadratic Zeeman effect. This implies that there is a quadratic relationship between the energy levels splits and the magnetic field B. This differs from the Zero-Field Transition as these relationships are linear. The resonance equation

$$\nu = g_F \mu_0 B/h, \tag{6}$$

which helps to determine the magnetic field at these resonance frequencies. The frequencies at which the absorption dips occur different for each isotope. Section IV will illustrate the differences between the resonant frequencies in the quadratic Zeeman effect. Under these conditions, we can expect two different absorption readings from the isotopes due to different I values. For I=3/2 , there will be six different dips. For I=5/2 , there will be ten. The absorption readings will help justify the results for the I values obtained for each isotope. The 2F+1 degeneracy is responsible for the difference in total dips in each isotope.

### C. Lande G-Factor

The Lande G-Factor is calculated using the equation

$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} \tag{7}$$

where

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \tag{8}$$

This experiment will allow the determination of the g-factor. By determining the g-factor, we will be able to calculate the angular momentum I.

### D. Rabi Flopping Oscillation

Rabi Flopping Oscillations occur when a two state system is taken out of equilibrium by an external driving

force. The electrons absorb the energy and jump between the ground state and the excited state.The Rabi frequency for a two-state system is written as

$$\frac{\Delta}{2} = \frac{1}{2}((\omega + \lambda B_o)^2 + \lambda^2 B_{RF}^2))^1/2, \quad (9)$$

where $\Delta$ is the Rabi frequency, $\gamma$ is the gyromagnetic ratio, and $\omega$ is the RF.

The electrons being analyzed make transitions to the M=2 sublevel. Rubidium 87 has two F levels 1 and 2 which are further split into M levels through the Zeeman effect.

## III. EXPERIMENT

The experimental set up is demonstrated by Figure 1. The experiment starts in the radio frequency discharge lamp. Inside the radio frequency discharge lamp is rubidium isotopes. A laser is directed at the ground state electrons of the rubidium isotopes. The electrons are brought to the excited state, then are released back down to the ground state. This causes photons to be released at 700 nm and 794.8 nm. These photons escape from the radio frequency discharge lamp and are directed towards the absorption cell of rubidium vapor. The interference filter only allows for the 794.8 nm photons to pass through, blocking the 700 nm photons. The remaining photons are then circularly polarized by two polarized lenses. The polarized photons are absorbed by the ground state rubidium isotopes in the vapor cell. The photons passing through are picked up by the detector on the other opposing side of cell. The information provided by the signal in the detector allow for the observation of the absorption dips for the hyperfine structure and the Zeeman splitting. It is important that the apparatus faces parallel to the Earth's north pole and south pole.

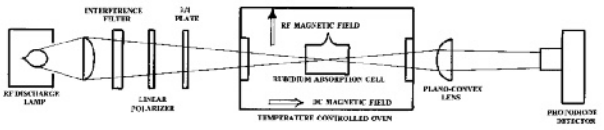



Figure 2. Experimental set up for Optical Pumping Experiment. RF discharge lamp and absorption cell both contain $^{85}$Rb and $^{87}$Rb. Absorption cell receives photons at 794.8 nm.

Magnetic fields are produced by Helmholtz coils surrounding the absorption cell. Two separate magnetic fields are produced by the Helmholtz coils: a vertical field and a horizontal field. The horizontal field is designed to cancel out the effects of Earth's magnetic field. The experimentalist knows he/she has achieved canceling out the magnetic field of the Earth when the Zero Field Transition is observed. This is done by varying the amount of current supplied to the horizontal field coils, which changes the magnitude of the magnetic field. The horizontal field points from the lamp to the detector. The horizontal sweep field is varied throughout the experiment. It starts from zero volts and is increased to the set voltage of the range. This allows the experimentalist to attain the full length of the absorption spectrum. The temperature setting is 50 Centigrade.

To obtain a wide range of results, readings were taken at varying frequencies. Explained in Section II, the RF is increased throughout the experiment in order to different absorption trends in the two isotopes of rubidium. The frequencies in this experiment range from 20 kHz to 1.5 MHz.

The last portion of the experiment aimed to solve the frequency of the Rabi Flopping Oscillation for $^{87}$Rb. RF was supplied to the rubidium electrons, being switched on and off with a frequency of 5Hz. By turning on the radio frequency, the electrons were taken out of thermal equilibrium, causing the Rabi Flopping Oscillation to occur. The voltage was varied to study whether the frequency of the oscillation would change. The radio frequency was kept at 220 kHz while the current was .11 amperes. The temperature remained at 50 Centigrade. Voltage was the variable changed with readings taken at 5, 7, and 10 volts.

## IV. RESULTS

The first data acquired for the experiment was the Zero Field Transition (previously described in the theory section). The larger dip is the zero field dip and the other dip can be ignored. This result is illustrated in Figure 4. The radio frequency was set to be 20 kHz. It was graphed using Matlab and shows the voltage versus the radio frequency. It shows where the horizontal magnetic net force is zero, canceling out the Earth's magnetic field. Uncertainties arise in our apparatus as it is difficult to be perfectly parallel with the Earth's north and south poles. Without perfect alignment, there may be a slight horizontal magnetic field that is unaccounted for. At this point, there was no current being supplied to the Helmholtz coils, thus the total magnetic field inside of the absorption chamber should be approximately zero. The incident beam from the RF discharge lamp was 794.8 nm. The 700 nm light was blocked by the interference filter.

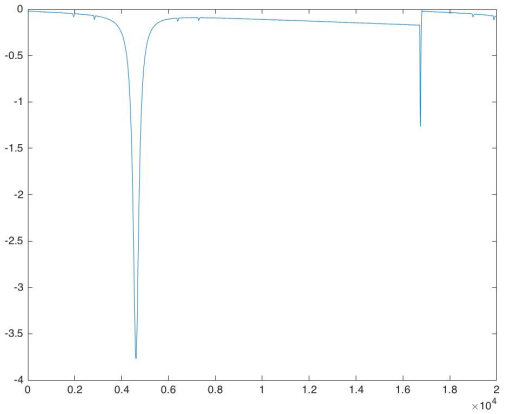



Figure 4. Shows the Zero Field Transition. Occurs when there no net magnetic field in the vertical or horizontal direction. This happens when the magnetic field of the Earth is the same as the magnetic field produced by the Helmholtz coils.

$^{85}$Rb has more angular momentum due to it's higher I value of 5/2. Based on this information, it was expected that this isotope of rubidium would have more Zeeman splitting than $^{87}$Rb. Both isotopes received an incident beam with a wavelength of 794.8 nm and a radio frequency of 5.4 MHz. Ten dips were observed and graphed using Matlab with the same axis described in Figure 4. In looking at the result, only eight downward dips are shown. The two other dips are going in the upward direction. The direction of the dips are irrelevant. Again, uncertainties arise in the set up of the experiment with the alignment of the apparatus.

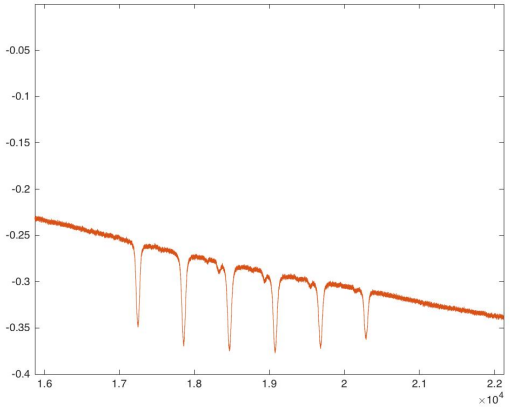



Figure 5. Shows the results of the quadratic Zeeman effect. Ten dips are shown in the figure with two dips going in the upward direction. The isotope shown is $^{85}$Rb.

As previously stated, $^{87}$Rb has a lower total angular momentum with an I value of 3/2. Using this information, it was predicted that there would be less observed dips in the absorption spectrum. Six dips were obtained in the experiment with a radio frequency of 5.4 MHz. The graph was created using Matlab with a voltage versus radio frequency lay out. The same uncertainties exist in these results as the last two. Four distinct dips are shown with two smaller dips towards the end of the sweep.

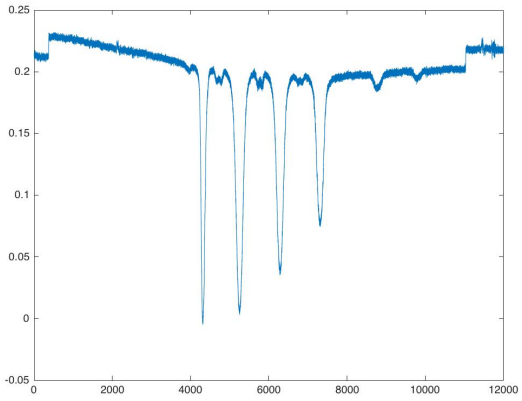



Figure 6. Shows the results of the quadratic Zeeman effect for $^{87}$Rb

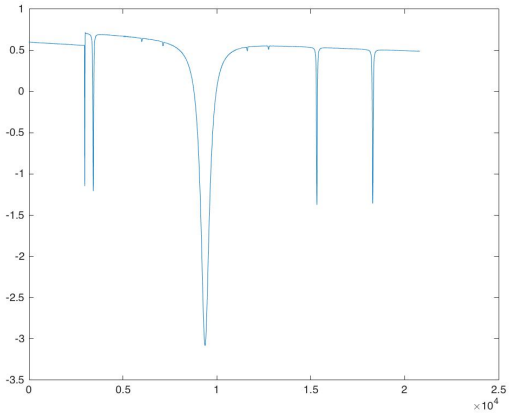



Figure 7. Shows the absorption spectrum of both isotopes. The first dip and last dip shows $^{87}$Rb and the two inside dips show $^{85}$Rb.

The calculation of the Lande g-factor was calculated by finding the Zeeman splitting at a range of different energy levels. By determining the value in which the minimum occurs for each isotope of Rubidium, two lines were generated using MatLab. Figures 8 and 9 illustrate the relation of each isotope with increasing frequency.

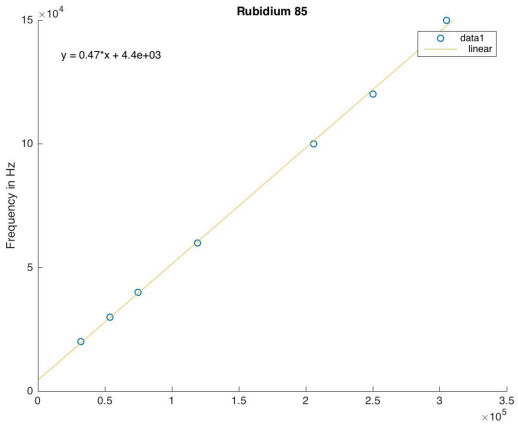



Figure 8. Graphing the frequencies of Rubidium 85 for each radio frequency reading. A best fit line was created and the equation of the line is displayed.

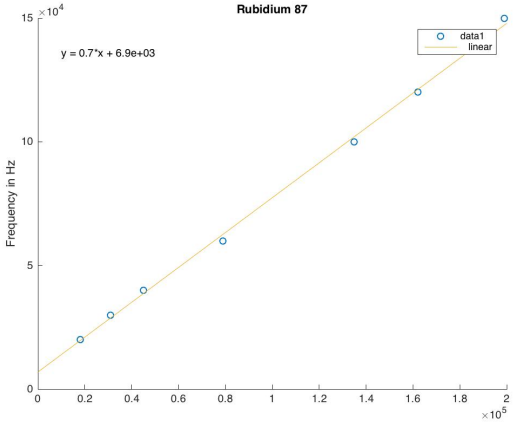



Figure 9. Frequencies of Rubidium-87 including a best fit line as well as the equation of the line.

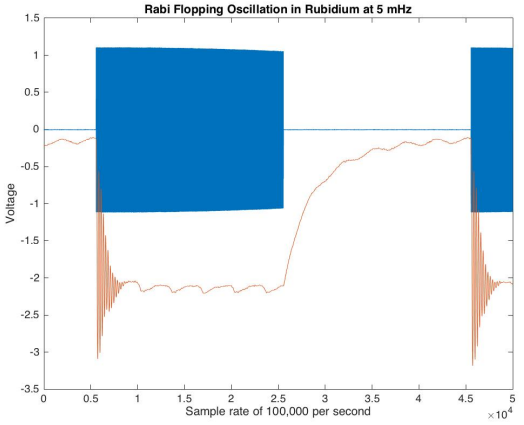
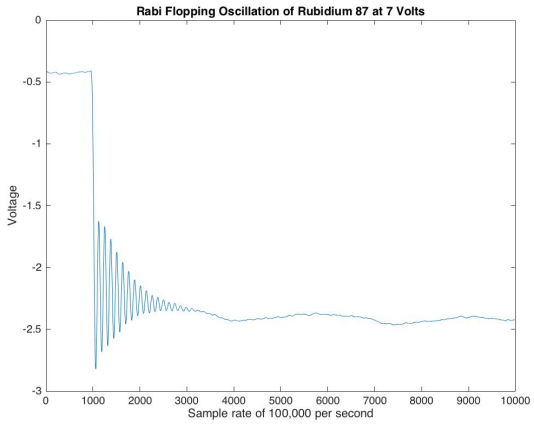



Figure 10. 5V Rabi Flopping Oscillation for $^{87}$Rb. Period of oscillation is 3.5 ± 0.3 ms. Blue section of the graph is the radio frequency which is supplied at a frequency of 5Hz with a radio frequency of 220kHz.




[Figure 11. 7V Rabi Flopping Oscillation. As illustrated, the frequency of the oscillation increased as the time period is 4.4 ± .3ms.]

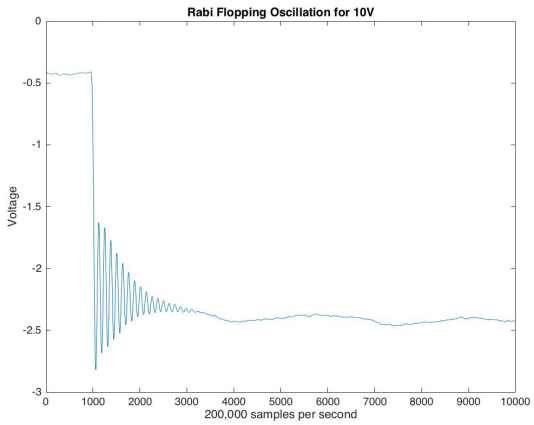



Figure 12. 10V Rabi Flopping Oscillation. Again, frequency of oscillation decreases due to an increase of voltage. The time period is measured to be 10.7 ± 3 ms.

The Rabi Flopping Oscillations were determined through different voltages. For the 5V system, the Rabi Flopping Oscillation had a time period of 3.5 ± .3 ms. For the 7V system, the Rabi Flopping Oscillation increased to 4.4 ± .3 ms. For 10V, the time period was measured to be 10.7 ± .3 ms.

## V. CONCLUSION

Our experiment was successful in showing the gradual changes of the g-factor as the radio frequency was changed overtime. Many uncertainties exist at the quantum level and many of which are difficult to quantify. Experimental error is easier to determine such as the alignment of our apparatus or other external magnetic fields disrupting our results. Optical pumping is one of several ways to determine quantum information such as the nuclear magnetic moment of an atom and the angular momentum.

For the Rabi Flopping Oscillation frequencies, the increase of the time periods as the voltage increases

fits theory. Oscillation increases because the perturbing magnetic field is stronger with a higher voltage. Uncertainties are very small for determining the time period for the oscillations. There would be error in the measurements of the time because the oscillation decay occurs very quickly. In looking at Figure 9, the radio frequency does not appear to be constantly at 220 kHz. Towards the end of the RF burst, the amplitude of the waves are slightly smaller than the amplitude of the wave when the burst begins. This would likely result in a smaller time period. The RF burst should look like a perfect rectangle when viewed from the zoom position of Figure 9. An even smaller uncertainty that always exists with working with magnets is the possibility of external magnetic fields that are unaccounted for in the data. Though small in comparison to the magnetic fields of the experiment, they are still capable of affecting the accuracy of the results.


[1] "Award Ceremony Speech." *Nobel Prize in Physics 1966.*

[2] A.C Melissions Jim Naplitano, *Experiments in Modern Physics,* 2nd. Ed

[3] Griffiths, David J., *Introduction to Quantum Mechanics,* 2nd. Ed

[4] "TeachSpin: Instruments for the Advanced Physics Laboratory." *TeachSpin: Instruments for the Advanced Physics Laboratory.*

[5] TeachSpin, *Optical Pumping of Rubidium OP1-A*

[6] Severn, Gregory, *Hyperfine Spectrum of Rubidium: Optical Pumping Experiments*

[7] Severn, Gregory, *Notes on Time Dependent Perturbation Theory (Rabi Flopping Oscillation)*