Optical pumping to observe the Zeeman effect under varying magnetic field strength

Hannah Saddler, Adam Egbert, and Will Weigand

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The first section of the experiment was designed to allow for calculations of the g-factor and quantum numbers of rubidium-85 and rubidium-87 at low magnetic fields. The second section of the experiment was designed to allow for measurable observations of the quadratic Zeeman effect at higher magnetic fields. In section one, the residual magnetic field was found to be 1.41 gauss at the zero-field point. This result was subtracted from subsequent data recorded to nullify the effects of Earth's magnetic field on the measurements. At the known value of 90 KHz and the weak measured magnetic fields of 0.87 guass and 2.78 gauss, the g-factors, g_f are 0.018 and 0.0115 for rb-87 and rb-85 respectively. The g_f values differed from the theoretical values of 1/3 and 1/2 by approximately a factor of 30; therefore we were unable to calculate reasonable values for the nuclear spins of the two isotopes. In stronger magnetic fields, there is a quadratic field dependence of energy levels on magnetic field seen in the Breit-Rabi Equation. The total magnetic fields at the resonances of the individual isotopes were measured and analyzed by comparing them to the theoretical values predicted by the Breit-Rabi equation. For rb-87, at 3.41 MHz the difference was (xx) gauss corresponding to (xx) percent. For rb-85, at 4.20 MHz the difference was (xx) gauss corresponding to (xx) percent.

I. INTRODUCTION

Optical pumping, in simple terms, is a method in which photons are pumped into a system to raise electrons from lower energy states to higher energy states. In optical pumping atoms or molecules are driven away from a thermodynamic equilibrium by means of resonant absorption of light. By using specific polarizations of light an individual can impose specific selection rules onto the light source to only allow certain dipole transitions. This allows one to effectively pump the whole source into a single metastable state.

The technique of optical pumping was developed by Alfred Kastler in the 1950s. Kastler went on to win a Nobel Prize in Physics for the discovery and development of optical methods for studying hertzian resonances in atoms in 1966. Optical pumping is a technology used in lasers, to precisely measure hyper-fine splitting in atoms, and to accurately measure weak magnetic fields. More recently this technology has been used to enhance magnetic resonance imaging techniques; optical pumping is used in the hyper-polarization of noble gases which is used for magnetic resonance imaging of the lungs and other organs.

There are two main components of this experiment. The intent of the first section of the experiment is to make measurements of low field resonances to calculate the quantum numbers of the two rubidium isotopes. The intent of the second section of the experiment is to make measurements of the quadratic Zeeman effect. The principal results of this section of the experiment will include current and total magnetic field measurements corresponding to each of the resonances. These results are compared to the total field calculated using the Breit-Rabi equation which is explained in a later section.

The following section will address and cover the theory behind the method of optical pumping. Section III is an overview of the experimental design and apparatus. Section IV is details the procedure and the results. Additionally this section includes a discussion of various equations and principles used to derive results from the data and a discussion of experimental and procedural errors incurred. Section V is a conclusion that ties together the results of the experiment to the usefulness of the technique of optical pumping.

II. THEORY

The atom rubidium was selected for this experiment because of its hydrogen-like qualities; rubidium can be approximated as a one electron atom because its core electrons form a noble gas configuration. This is seen in its electronic configuration:

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

The valence electron can be described by is orbital angular momentum L, spin angular momentum S, and total non-nuclear angular momentum J. Additionally each of these angular momenta has a magnetic dipole associated with it.

Just like in classical angular momentum, the different orientations of the vector lead to different interaction energies. The ground state of an alkali atom is designated $^2S_{1/2}$ and the first excited state is a P state. In the P state, however J can have values L+S and L-S so there are exactly two P states : $^2P_{1/2}$ and $^2P_{3/2}$. The energy splitting between these two states is called the Fine Structure. Additionally one must look at the properties of the nucleus; the nucleus has spin and a magnetic dipole moment due to the intrinsic spin of the nucleus. The nuclear spin is labeled I and the interaction is $\mu_I \bullet \mu_j$; the interaction of these two results in another splitting of the energy levels call hyperfine splitting.

The effect of a weak external magnetic field on the energy levels on the rubidium atom produces the Zeeman

Effect. The Zeeman Effect is the further splitting of the energy levels in the presence of a weak, static magnetic field. The applied magnetic field splits each F level into 2F+1 sub-levels that are equally spaces, where F is the total angular momentum of the atom. The energy levels of the atom can be calculated from quantum mechanics. Since the electron is bound in the atom, the effective magnetic moment is changing and can be described by its Lande g-factor. The Lande g-factor, g_f is given by Eq. 2.

$$g_j = \frac{((L+2S) \bullet J)}{J^2} \tag{2}$$

Since the interaction with the nucleus must be taken into account a new quantity is needed. The measured g-factor, g_f is given by eq 3.

$$g_f = g_j \frac{(F(F+1) + J(J+1) - I(I+1))}{(2F(F+1))} \tag{3}$$

The interaction energy is then given by

$$W = g_f \mu_0 BM \tag{4}$$

Equation 4 is applicable in small magnetic fields were the energy level dependence is linear. However stronger magnetic fields produce a quadratic dependence seen in Eq 5

$$W(F,M) = \frac{-\Delta W}{2(2I+1)} - \frac{\mu_I}{I} BM \pm \frac{\Delta W}{2}[1 + \frac{4M}{2I+1}x + x^2]^{1/2} \tag{5}$$

where

$$x = (g_j - g_I)\frac{\mu_0 B}{\Delta W} \tag{6}$$

$$g_I = \frac{-\mu_I}{I\mu_0}. \tag{7}$$

In the optical pumping experiment, one is concerned with small magnetic fields where the levels are either linearly or quadratically dependent on magnetic field.

Electric dipole transitions can take place is following specific selection rules. The transitions taking place between the S and P states are governed by the following rules:

$$\Delta S = 0, \Delta J = 0, \pm 1, \Delta L = 0, \pm 1. \tag{8}$$

One must also take into account the hyperfine structure and the Zeeman effect at applied magnetic fields so two additional rules arise:

$$\Delta F = 0, \pm 1, \Delta M = 0, \pm 1. \tag{9}$$

However since the $\Delta F = \pm 1$ transition occurs only at very high frequencies one will only be concerned with $\Delta F = 0$ and $\Delta M = \pm 1$.

As stated previously, optical pumping is a method of driving atoms away from thermodynamic equilibrium by means of resonant absorption of light. The resonance light is produced by an RF discharge lamp that contains a small amount of rubidium metal and xenon gas. A noble gas is used to buffer the rubidium atoms because collisions with the walls will destroy optical pumping very quickly. [2] [3]

III. EXPERIMENTAL DESIGN

The experimental setup has several key components. Figure 1 is a schematic diagram of the experimental setup.

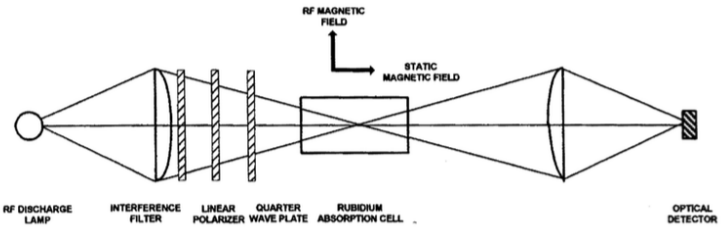

FIG. 1. Diagram of Experimental Setup for Optical Pumping

There is an RF discharge lamp, interference filter, linear polarizer, quarter-wave plate, rubidium absorption cell, and optical detector. As stated previously, optical pumping is a method of driving atoms away from thermodynamic equilibrium by means of resonant absorption of light. The resonance light is produced by an RF discharge lamp that contains a small amount of rubidium metal and xenon gas. A noble gas is used to buffer the rubidium atoms because collisions with the walls will destroy optical pumping very quickly.

Resonance light from the lamp consists of two main lines at 780 nm and 795 nm. The interference filter is used to subtract out the 780 nm lime. The light is then linearly polarized as it passes through the linear polarizer. The light then becomes right circular polarized as it passes through the quarter-wave plate. This step is necessary because it specifies a selection rule that $\Delta M = +1$ and the light must be circularly polarized before going through the rubidium absorption cell. The optical detector then measures the intensity of the transmitted light. A uniform dc magnetic field is applied at the absorption. Dipole transitions are induced in the rubidium sample by the RF magnetic field. The electric dipole transitions are induced by the optical radiation and magnetic dipole transitions between the Zeeman levels are induced by the RF magnetic field. The RF magnetic field is applied perpendicular to the dc magnetic field.

IV. DISCUSSION

The entire experiment was divided into two main sections: low field resonances and the quadratic Zeeman effect. The the entirety of the experiment the temperature cell was set to 320 K and before any experimentation began a thermodynamic equilibrium was established by waiting for the cell to slowly heat up. The first step of the experiment was to observe the zero-field transition. There no was RF applied and the horizontal field coils were set to zero; the vertical field was adjusted to achieve minimum width of the zero-field transition. The current was measured at the zero-field transition to be 2.34 A. The current was used to calculate the magnetic field as seen in Equation 10

$$B(gauss) = 8.991X10^{-3}IN/\vec{R}. \tag{10}$$

For this particular experimental apparatus the mean radius, $\vec{R}$, was equal to 0.1639m and the number of turns on each side, N, was equal to 11. The calculated residual magnetic field was 1.41 gauss. This represented the magnetic field applied in the opposite direction of Earth's magnetic field necessary to nullify it; the value of the residual magnetic field was subtracted from the subsequent results because the rest of the experiment was done in the opposite orientation of magnetic field. The measured value of 1.41 gauss differs significantly from the known values of 0.25-1 gauss for Earth's magnetic field. The inconsistency of the data may be the result an unaccounted value of dc magnetic field being applied to the system through the Helmholtz coils unknowingly. The significant amount of error in this measurement impacted the subsequent measurements of g-factors and nuclear spins for the two rubidium isotopes.

The low field resonances of the two rubidium isotopes were analyzed at increasing RF fields. The data recorded was the sweep voltage corresponding to each isotopes' resonance peaks at an applied RF frequency. Figure refLFR shows the zero field transition and the two resonance peaks for the two rubidium isotopes. The data was plotted in Figure 3 to confirm that the Zeeman effect was linear at low fields. The ratio of the slopes of each isotope was calculated to be 1.54. The predicted value of the ratio of slopes is 1.5; therefore the difference in results suggests at 4.0 percent error. This difference could be attributed to error in selecting the sweep value corresponding to the minima. At a chosen frequency of 90 KHz the measured currents of the two isotopes were 3.775 A and 6.9374 A which corresponded to 2.28 gauss and 4.19 gauss. The residual field of 1.41 gauss was subtracted yielding 0.87 gauss for rb-87 and 2.78 gauss for rb-85. Using the resonance equation shown below in Eq 11 the g_f values can be calculated.

$$\nu = g_f \mu_0 B/h \tag{11}$$

The resulting g_f values are 0.018 and 0.0115 for rb-87 and rb-85 respectively. Using the g-factor and the Lande g-factor, g_J, values for spin calculated and compared to the theoretical values. The equations for g_J and g_f go as follows:

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \tag{12}$$

$$g_f = g_j \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)}. \tag{13}$$

The theoretical values for g-factor are 1/3 and 1/2. The measured data and the theoretical values differ by a factor of approximately 30. The significant error can be largely attributed to the large error resulting from the residual magnetic field measurements. As a result of the large difference between the theoretical and measured values for g-factor, nuclear spins for the two isotopes were unable to be calculated. With g-factor values of 1/3 and 1/2. the nuclear spins should have been calculated to be 5/2 and 3/2.

The second section of the experiment involved analyzing the region where the RF resonances of both isotopes under an applied magnetic field are no longer linearly related to the energy level splitting. Each of the zero field energies are split into 2F+1 sublevels. For the I=3/2 spin there are six total resonances and for the I=5/2 spin there are ten total resonances that can all be observed. The magnetic field at which these resonances can be observed can be estimated from the resonance equation seen in equation 11. The currents from each resonance were recorded from which the magnetic fields were determined. The magnetic fields for each resonance were also calculated using the Breit-Rabi equation using the known quantum numbers for the isotopes. The B-R equation was solved for total magnetic field.

The measured magnetic fields for each resonance were compared to the calculated magnetic fields for each resonance. The results for the rb-85 isotope are given in Fig **??**, Fig **??**, and Table **??**. Based upon the results, the difference between the measured and calculated magnetic fields is XX gauss which corresponds to XX percent. The results for the rb-87 isotope are given in Fig **??**, Fig **??**, and Table **??**. Based upon the results, the difference between the measured and calculated magnetic fields is XX gauss which corresponds to XX percent.

V. CONCLUSION

The results from the multiple different measurements made during this experiment indicate the various values that can be calculated from optical pumping and some of its applications. Both parts of the experiment indicate the interaction of the Zeeman effect and how its effects differ in varying strengths of applied magnetic fields. As seen in the first part of the experiment, optical pumping

can be useful in calculating spin values and other quantum properties of unknown atoms. Unfortunately the significant error due to the incorrect measurement of the residual field prevented us from being able to calculate reasonable g-factor and spin values. The second part of the experiment allowed us to observe the quadratic Zeeman effect. By measuring and recording the total magnetic fields for each resonance and comparing them to the calculated total magnetic field values, it is apparent that optical pumping is a method that can be used to measure fine magnetic fields.

VI. ACKNOWLEDGEMENTS

I would like to thank Dr. Severn for the opportunity to experimentally experience the quantum and optical physics previously learned in a solely theoretical manner. Dr. Severn was also instrumental in guiding and helping with the theoretical knowledge necessary to perform this experiment. I would also like to thank my lab partners Adam Egbert and Will Weigand for their help with carrying out the experiments and data analysis.

[1] *Optical Pumping of Rubidium OP1-A : Guide to the Experiment* Teach Spin.
[2] David J Griffiths. *An Introduction to Quantum Mechanics* Pearson Prentice Hall, India, (2004).
[3] William Happer. *Optical Pumping* Reviews of Modern Physics, APS, (1972).

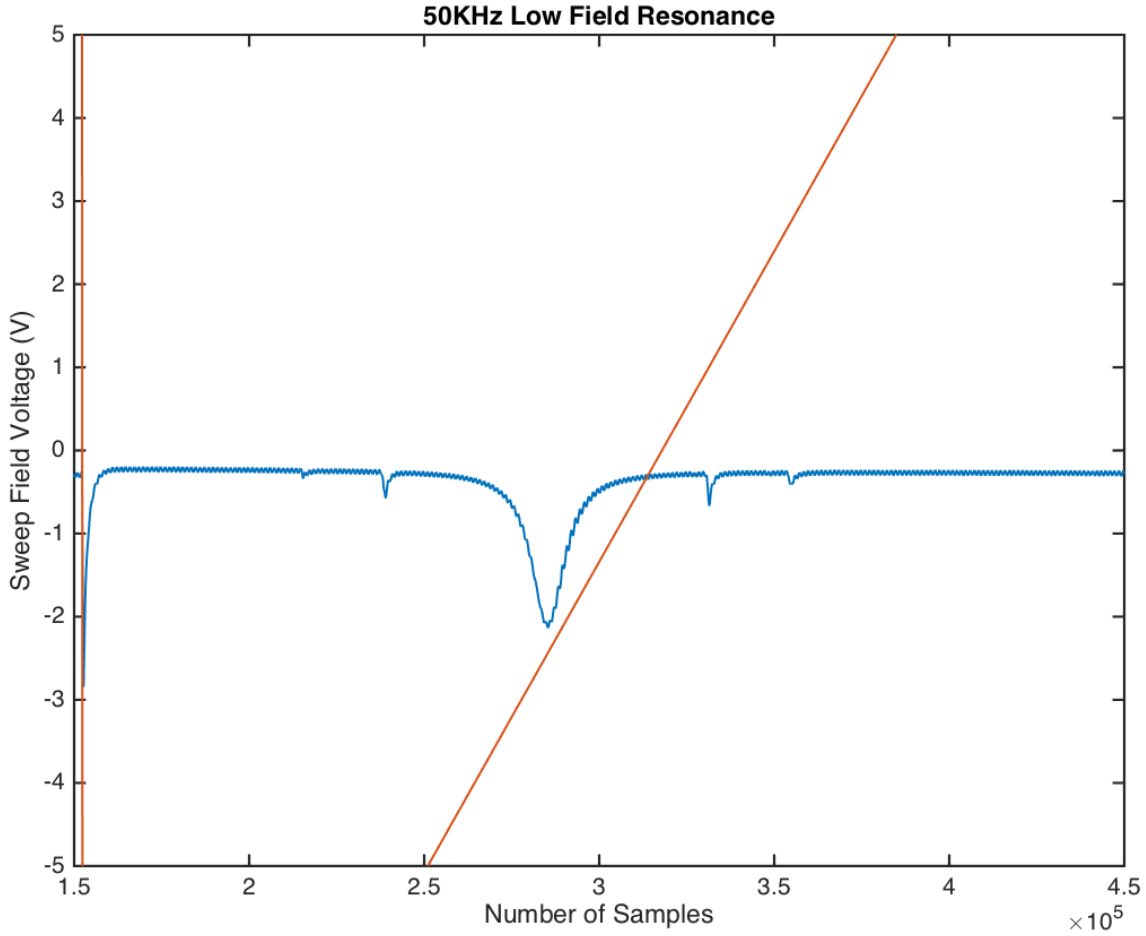

FIG. 2. Plot showing the resonances of rb-87 and rb-85 at low magnetic fields. The y-axis is the transmitted light intensity measured in voltage and the x-axis is the magnetic field measured in amps. The measured currents at each of the resonance peaks is used to determine the g-factor and spin values for each isotope.

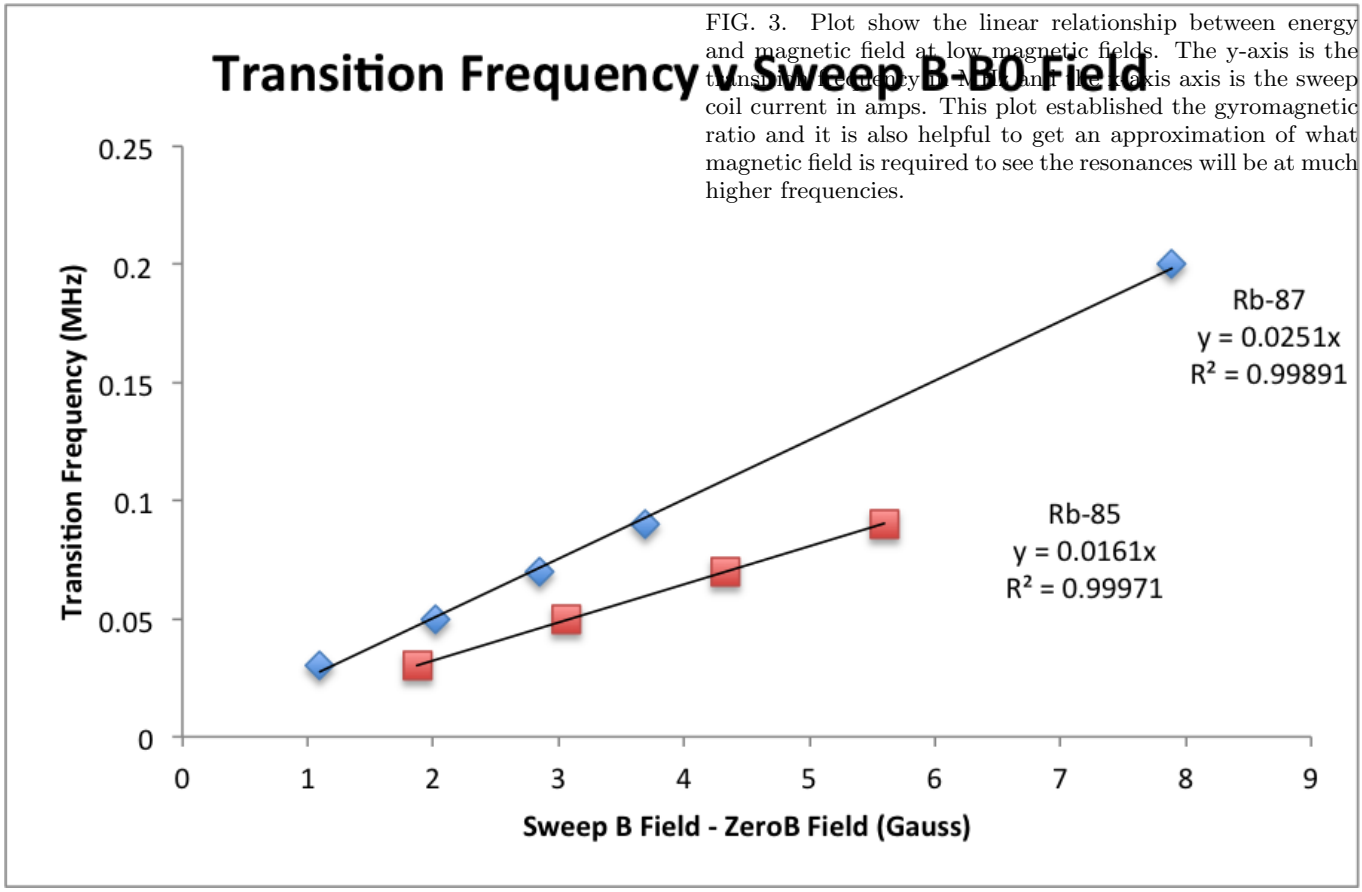

FIG. 3. Plot show the linear relationship between energy and magnetic field at low magnetic fields. The y-axis is the transition frequency in MHz and the x-axis axis is the sweep coil current in amps. This plot established the gyromagnetic ratio and it is also helpful to get an approximation of what magnetic field is required to see the resonances will be at much higher frequencies.