Optical Pumping

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1 Introduction

Optical pumping is a powerful experimental technique that will be used in this experiment to look into specific atomic energy states of Rubidium atoms in a vapor cell. The technique of optical pumping will be used to make precise measurements of magnetic fields, explore the atomic energy level structure of an atom, and make measurements of the energy of Zeeman splitting. Atoms occupy discrete energy states, and the relative numbers in each state can become non-Boltzmann-distributed if a light of appropriate energy and polarization cause atoms to go into an excited state which they cannot escape. More specifically, this light will shine through a vapor cell of Rubidium atoms (a mix of the 85 and 87 isotopes), and the effects will be measured through an oscilloscope.

Before the analyses are done, it is relevant to mention how the apparatus was set up. There is an ambient magnetic field, coming from the Earth but also the building in which the experiment was done, and this must be canceled using horizontal and vertical magnetic field generators. The vertical field is a fixed value, whereas the horizontal field sweeps - it is important to align the apparatus such that the ambient magnetic field could be canceled out in just these two dimensions. The magnetic field generated from the apparatus can be approximated using Equation 1,

$$B = \frac{0.8991 * 10^{-6} nI}{R} \tag{1}$$

where B is the magnetic field, n is the number of turns in the field coils, I is the current, and R is the radius of the Helmholtz coils. Initial guesses of the ambient magnetic field can be based upon the Earth's field near Chicago, and the input current can then be solved for and applied to attempt to cancel out the ambient magnetic field. Tweaks are made in alignment and the fields applied to vertical Helmholz coil, using the horizontal sweep ability where the de-pumping signal should be sharp and deep. This result was seen on the oscilloscope, and with this it became possible to observe the effects of Zeeman splitting in higher detail.

2 Results

Broadly, the results are based around the Zeeman effect, where both weak field and strong field effects will be observed. The mix of two isotopes will also become clear in this analysis, where the applied photons from the RF coils will induce electronic transitions that deviate the electrons from the strictly pumped state. Note that a left circularly polarized light is used throughout that is parallel to the applied magnetic field, which allows for only certain transitions and causes a pumped state if there is a magnetic field present.

2.1 Zeeman Splitting in the Small Field Approximation

Before observing the energy splitting of the two isotopes of Rubidium, it is first important to obtain a calibration between the voltage of the applied horizontal sweep field and what was read out on the oscilloscope. This was done by using a volt meter on the apparatus, where it was possible to find the voltage in the horizontal sweep field by attaching the volt meter in parallel. By fixing the sweep range to 0, the horizontal field did not actively "sweep," which allowed for being able to read a voltage on the volt meter and what that input read out as on the volt meter for a range of constant values. The voltages used for calibration are shown in Table 1.

Oscilloscope (V)	**Volt Meter (V)**
-8.4 ± 0.1	0.267 ± 0.001
-2.2 ± 0.1	0.473 ± 0.001
2.4 ± 0.1	0.620 ± 0.001
5.2 ± 0.1	0.718 ± 0.001
13.0 ± 0.1	0.977 ± 0.001

Table 1: Voltages read off from the oscilloscope and the volt meter used to perform calibration.

These numbers were used to create an accurate calibration, which would consider the oscilloscope voltage reading to an actual voltage reading. This will be used later on, as measurements were taken from the oscilloscope but real voltage values were required. The calibration is shown in Figure 1.

The calibration presents the results needed for upcoming analyses. The calibration factor for the horizontal sweep field is expressed in Equation 2,

$$\text{horizontal voltage} = 0.03308 * (\text{oscilloscope reading}) + 0.5452 \tag{2}$$

Now with this calibration handy, values read off from the oscilloscope can be converted to physical voltages. The horizontal sweep field is re-applied, and it is clear there is a zero-magnetic field point where the applied horizontal magnetic field from the Helmholtz coils cancels out the ambient magnetic field. This is shown by a sharp dip on the oscilloscope, as the rubidium atoms are able to

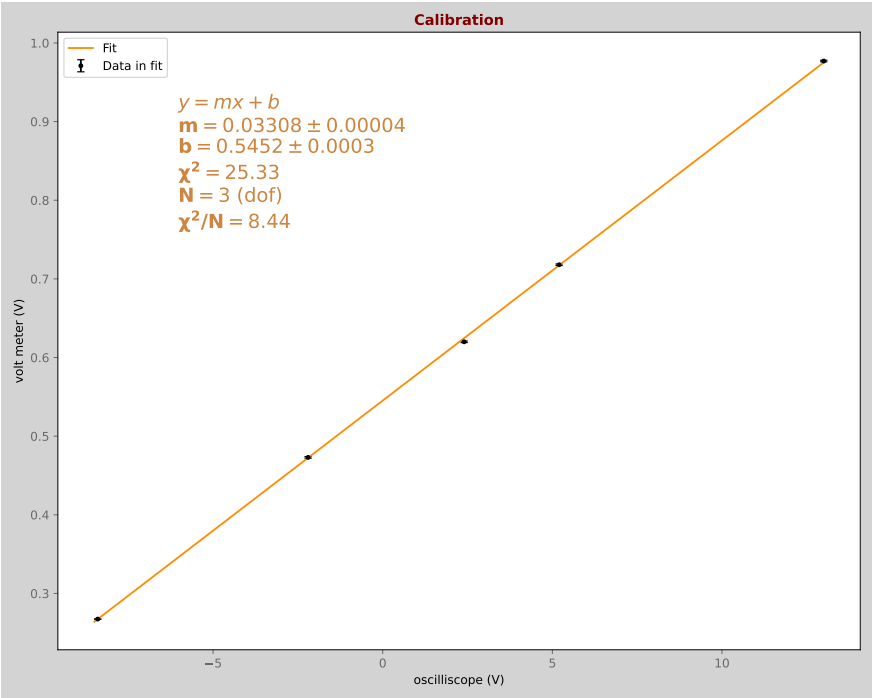

Figure 1: Calibration factor for the horizontal sweep field.

suddenly absorb the polarized light without any net magnetic field present, as they are depumped. With use of a function generator, RF coils that generate RF photons are turned on, which use a sine wave from the function generator. Gas that is in a pumped state, with an applied RF field, can cause electrons in the pumped state to be driven into a different state, causing the gas to be depumped for a certain isotope. An example of a typical trace with an arbitrary RF frequency is shown in Figure 2.

A few features are important to note in Figure 2 - the B=0 dip is the largest of all, this is where all the isotopes become not affected by an ambient magnetic field, and therefore become depumped and can absorb photons from the polarized light. Because of the way that the instrument works, there is a quick sweep that happens to go from the maximum back to the minimum of the horizontal applied voltage, and this quickly sweeps over the points in voltage that show reduced transmission, hence the small dips that occur at the beginning and end in Figure 2. On either side of the B=0 dip, there are two different smaller dips that are caused by including the RF coils sine wave at a certain frequency. One peak corresponds to a specific isotope of the Rubidium, and the relative abundances suggest that the larger peak corresponds to ^{85}Rb and the smaller peak corresponds to ^{87}Rb, and this will be experimentally proven in the next section when looking at large field Zeeman splitting. The higher abundance of

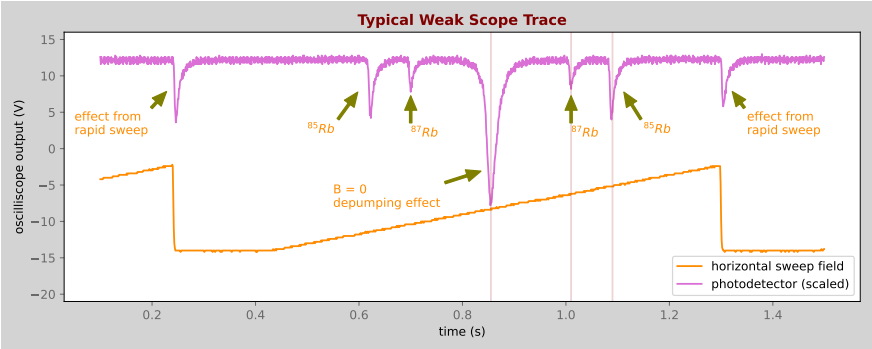

Figure 2: A typical trace in RF depumping oscilloscope data. Note the y-axis only applies to the horizontal sweep field; the values for the incident photons are scaled for visibility.

^{85}Rb isotope means more atoms in the vapor are depumped, and more light is absorbed, causing a larger dip.

The peaks are different for the different isotopes because they have different nuclear spins, which cause different Zeeman resonances; when energy of the RF photons matches the energy difference between the Zeeman energy levels, the isotope becomes depumped and can absorb some incident light. Two symmetrical dips appear, on either side of the B=0 dip, for each isotope. This is because the dips are the same absolute magnetic field difference away from 0 for a given isotope, and the RF frequency can cause depumping to happen either by creating imbalance in lower to higher energy levels or higher to lower energy levels. This symmetry can be exploited, and only one side of the B=0 magnetic field needs to be used. Changing the frequency of the RF coils changes the energy of the RF photons, which then changes where resonance occurs for each isotope. Using a changing frequency in the RF coils, it is possible to record the voltage and therefore magnetic field compared to the B=0 point where resonance occurs for each isotope. From the trace, like one in Figure 2, the measured values are oscilloscope volts which must be converted to real volts and then a net magnetic field using the Helmholtz coil equation. For select input frequencies of RF photons, the recorded oscilloscope values where resonance occurs on the net magnetic field are shown in Table 2. The 3 measured voltages are visualized in Figure 2, where the brown vertical lines represent the points where the horizontal sweep field is measured.

Table 2 is purely observational, but these values undergo calibrations and conversions before being able to plot E of the RF photons versus the B_{net} relative to the zero field depumping signal. RF energy, E, is simply calculated using the equation $E = h * f$ where h is Planck's constant and f is frequency in Hz. The calculation to get B_{net} is more involved. First, the voltages read out from the oscillator must be converted to physical voltages using the calibration defined in Equation 2. Next, the voltages must become net voltages; where the

RF Freq (kHz)	**B=0 (V)**	^{85}Rb **(V)**	^{87}Rb **(V)**
20	-8.2 ± 0.1	-6.2 ± 0.1	-7.0 ± 0.1
30	-8.2 ± 0.1	-5.2 ± 0.1	-6.2 ± 0.1
40	-8.2 ± 0.1	-4.0 ± 0.1	-5.6 ± 0.1
50	-8.2 ± 0.1	-3.2 ± 0.1	-5.0 ± 0.1
70	-8.2 ± 0.1	-1.0 ± 0.1	-3.4 ± 0.1
90	-8.4 ± 0.1	1.2 ± 0.1	-2.0 ± 0.1
110	-8.0 ± 0.1	3.2 ± 0.1	-0.8 ± 0.1
130	-8.2 ± 0.1	5.2 ± 0.1	1.0 ± 0.1
150	-8.4 ± 0.1	7.4 ± 0.1	2.2 ± 0.1

Table 2: Horizontal sweep field oscilloscope voltages (not calibrated) for the B=0 and isotope resonances for given RF frequencies.

zero field depumping signal becomes a zeropoint as that is where there is truly no horizontal magnetic field. Finally, these votlages can be used to calculate B_{net} as defined for a Helmholtz coil in Equation 1. For the horizontal sweep coils, n is 11 turns and the radius is 0.164 meters. Note that voltage is directly proportional to current amplitude in this experiment. Using this context, one can now calculate E of the RF photons versus the B_{net} relative to the zero field depumping signal, and these results are shown in Table 3.

RF Energy (eV)	$^{85}Rb\,B_{net}$ **(G)**	$^{87}Rb\,B_{net}$ **(G)**
1.65e-10	1.60	0.99
2.07e-10	1.90	1.22
8.27e-11	0.76	0.46
1.24e-10	1.14	0.76
6.20e-10	6.02	4.04
5.38e-10	5.10	3.50
4.55e-10	4.27	2.74
3.72e-10	3.66	2.44
2.90e-10	2.74	1.83

Table 3: E of the RF photons and the B_{net} relative to the zero field depumping signal, calculated from observational values in Table 2

Fits can be done for each, relating E and B_{net}. The fits are shown in Figures 3 and 4. It is convenient to use B_{net} as x and E as y, as this would allow for simple calculation of the Landé g-factor, g_f. This is given by Equation 3,

$$E = -\vec{\mu} \cdot \vec{B} = g_f \left(\frac{e}{2m_e}\right) \vec{F} \cdot \vec{B} = g_f \left(\frac{e\hbar}{2m_e}\right) B m_F \tag{3}$$

Where the factor $\mu_B = \left(\frac{e\hbar}{2m_e}\right) \approx 5.7883 * 10^{-9}$ eV/G. With this factor, all

that is left is $E = g_f \mu_B B m_F$. m_F in this case is equal to $+1$, and therefore the slope of the fits are $= g_f \mu_B$. The resulting g_f values are therefore 0.0178 for ^{85}Rb and 0.0261 for ^{87}Rb.

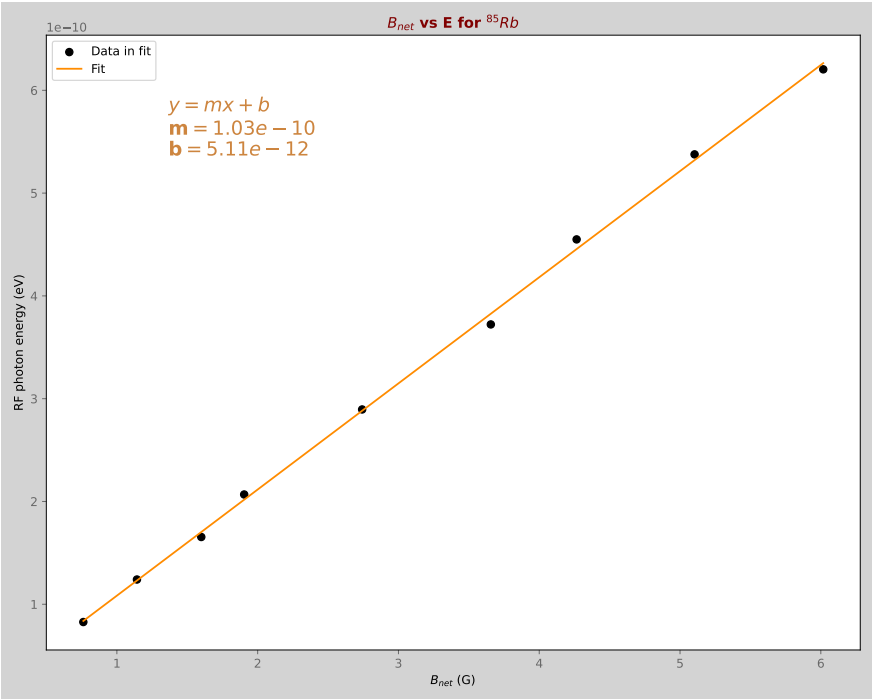

Figure 3: E of the RF photons and the B_{net} relative to the zero field depumping signal for ^{85}Rb

The theoretical model for the Landé g-factor, g_f, use Equations 4,

$$g_f = g_j \frac{f(f+1) + j(j+1) - i(i+1)}{2f(f+1)} \tag{4}$$

, and Equation 5,

$$g_j = 1 + \frac{j(j+1) + s(s+1) - \ell(\ell+1)}{2j(j+1)} \tag{5}$$

Using theoretical knowledge, these values are solvable and can be used to solve for the theoretical Landé g-factor, g_f. l is the orbital angular momentum, s is the spin of the electron, and j is the sum of the two in Equation 5. For all Rubidium isotopes, the spin $s = \frac{1}{2}$ and $l = 0$ for electron in ground state, and $j = \frac{1}{2}$. This means that $g_j = 2$ for both isotopes. Now, g_f can be calculated. i is different for each isotope because of the different number of neutrons; it is 5/2 for ^{85}Rb and 3/2 for ^{87}Rb. f is the addition of i and j. Therefore, according to Equation 4, $g_f = \frac{1}{3}$ for ^{85}Rb and $g_f = \frac{1}{2}$ for ^{87}Rb.

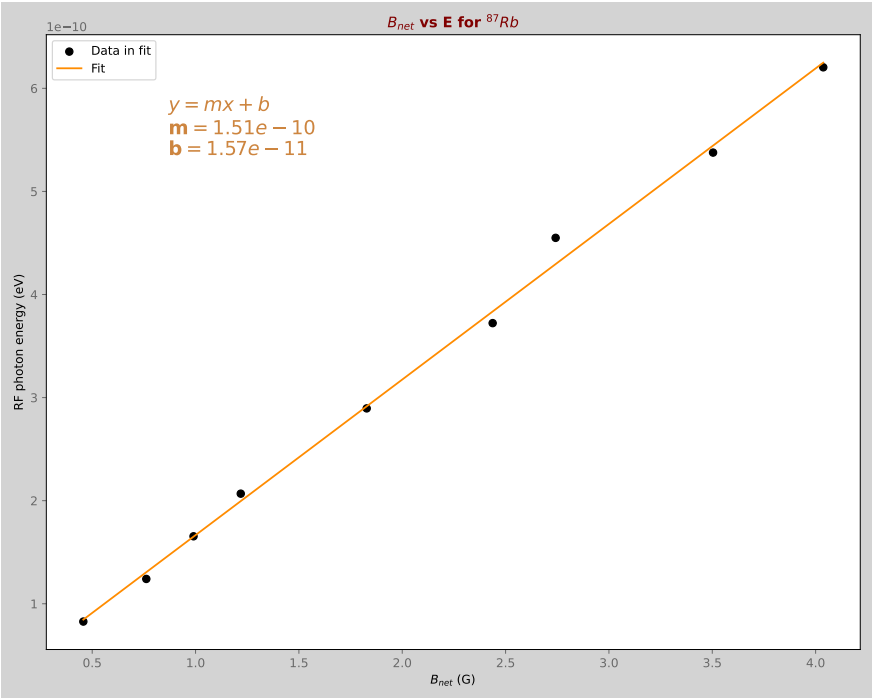

Figure 4: E of the RF photons and the B_{net} relative to the zero field depumping signal for ^{87}Rb

It appears that the theoretical values are significantly different than the experimental ones; however, the ratios between the two are very close. The theoretical g_f ratio with $^{85}Rb/^{87}Rb$ is $\frac{2}{3}$, and the experimental g_f ratio is $\frac{0.0178}{0.0261} = 0.682$. These ratios are reasonably close, which suggests that there is a common factor impeding with the experimental results. This factor is around 19, and it could source from improper calibration or incorrect unit conversion. In general, the experiment of optical pumping with RF photons has been proven that it can be used to calculate g_f factors, which can be used to learn more about the quantum properties of an isotope.

2.2 Large Field Zeeman Splitting

Now with the context of RF depumping, one can explore the Zeeman splitting at high magnetic fields, which is also known as large field Zeeman splitting. There are extra Helmholtz coils that are powered by a power supply that induce a stronger magnetic field in the horizontal direction, the same direction as the horizontal sweep. With the horizontal sweep still happening, and increasing the magnetic field, the entire sweep is basically shifted up the slope, meaning the depumping signals can be lost. However, from the last section, it was

understood that applying a higher frequency to the RF photons causes the depumping resonance dip to shift further away from the B=0 point. By both increasing the B and increasing the RF frequency simultaneously, the dip can stay within the oscilloscope to examine what happens to a certain isotope's resonance when the magnetic field gets very large. The dips for each isotope become very separated with large RF frequencies, so this analysis followed one isotope at a time.

Following the last dip of RF resonance for isotope ^{85}Rb, the strong effect was eventually observed when the power input was 13.4 V and the frequency of the RF photons went up to 5.1 MHz. The second to last dip was now far left, so increasing the frequency even more eventually also brought it into screen. According to Figure 5, it is clear that there are 6 different dips for ^{85}Rb, and for Figure 6 it is clear that there are 4 different dips for ^{87}Rb. In both figures, these peaks are marked with green arrows, where optical depumping is present with higher light absorption at those locations compared to the continuum.

Originally, the Zeeman levels in an energy level diagram basically create a normal distribution at low magnetic fields where the difference between one level and another are blended together. With larger magnetic fields, the distance starts to quadratically change between the Zeeman levels, which causes each of the Zeeman levels to become individually observable in its effects of depumping. Since nuclear spin is directly related to these levels, one could use Equation 6 to deduce the nuclear spin I of an isotope.

$$\#\text{ of peaks} = 2I + 1 \tag{6}$$

This equation makes sense because nuclear spin allows for each of the zero field energy levels to split into a certain number of peaks, which are symmetrical around a 0 level. Using this equation, one can derive the nuclear spin I for both isotopes of Rubidium: $I = \frac{5}{2}$ for ^{85}Rb, and $I = \frac{3}{2}$ for ^{87}Rb. This is a way to experimentally confirm that the last peak is indeed ^{85}Rb, which supports the previous claim based on simply the abundance of the isotope. This experiment can be used for other mixes of isotopes with other atoms, especially when their mixture is not entirely clear.

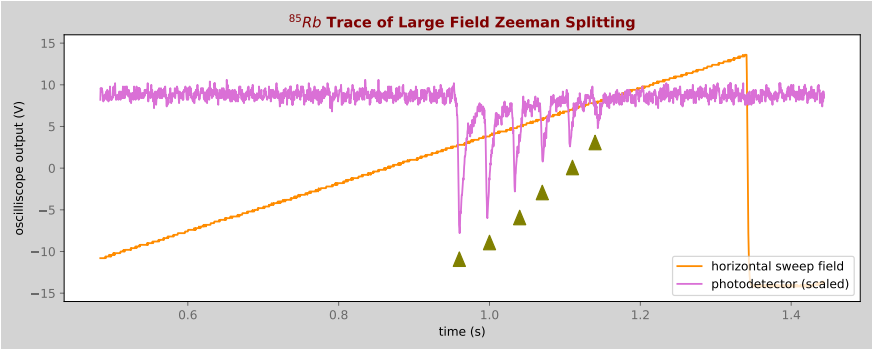

Figure 5: Scope trace for large field Zeeman splitting for isotope ^{85}Rb.

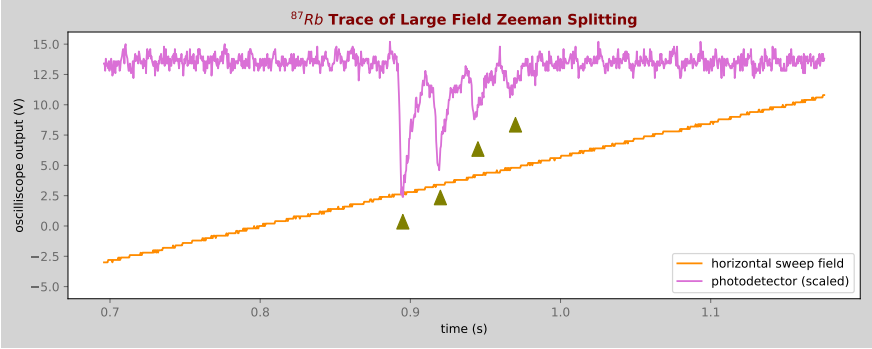

Figure 6: Scope trace for large field Zeeman splitting for isotope ^{87}Rb.