Optical Pumping of Rubidium OP1-A

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Abstract

The goal of this experiment is to measure the Zeeman splitting of rubidium atoms in a magnetic field and to find the experimental values for g_F values for the isotopes of rubidium; ^{85}Rb and ^{87}Rb.

I. INTRODUCTION

In quantum mechanics, hydrogen-like atoms, i.e. atoms with only one valence electron, are modeled such that the outmost electron can only exist in some discrete energy levels. These orbits are described by quantum numbers n and l, where $n = 1, 2, ...$ and $l = s, p, d, f, ...$, denoting the energy and orbital angular momentum of the electron. However, this model does not consider the spin of the electron. When the spin is taken into account, each energy level will split into two due to the coupling effect between the spin and the orbital angular momentum of the electron. This is known as the fine structure. The summation $J = L + S$ is the total angular momentum, where S is the electron spin and L is the orbital angular momentum. If the spin of the nucleus I is also considered, each fine-structure level will again split. And the atom will have a total angular momentum $F = I + J$. This is also known as the hyperfine structure. Finally, when a relatively weak external magnetic field is applied, each F level splits into different M levels with spacing proportional to the strength of the field. This splitting is known as the Zeeman effect. The Zeeman splitting is given by

$$E_z = g_F \mu_0 B M \tag{1}$$

Where E_z is the Zeeman energy, the energy difference between two different M levels, B is the external magnetic field strength, and μ_0 is the Bohr magneton. From Eq. (1) it can be seen that E_z is linearly proportional to B. By changing the RF signal, which will match E_z, and the magnetic field B, we could find out the coupling constant g_F for Rubidium.

$$\mu_0 = \frac{e\hbar}{2m_e} = 9.27 \times 10^{-24} J/T \tag{2}$$

And g_F is the coupling constant, known as the Lande g-factor.

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

and

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \tag{4}$$

Fig. 1 shows the Zeeman splitting of a Rubidium 87 atom.

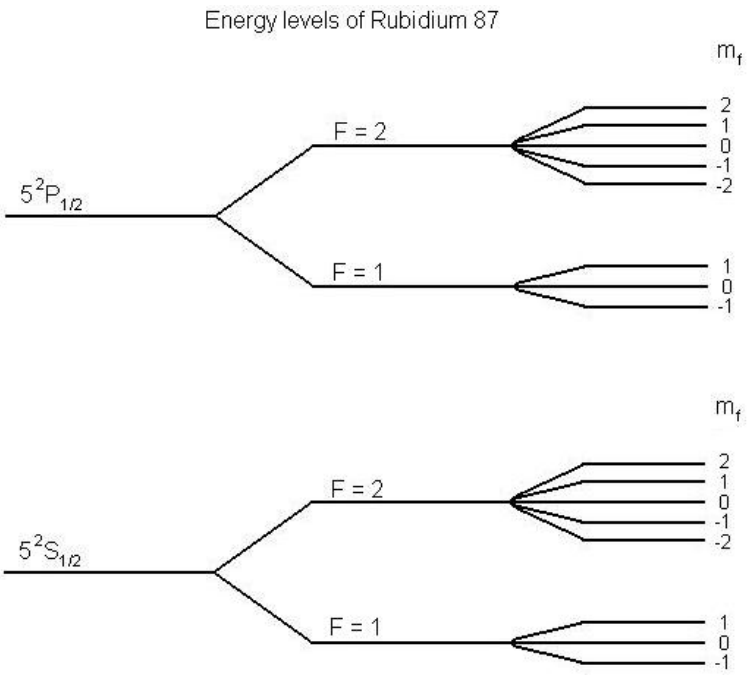

FIG. 1. Zeeman splitting of Rubidium 85 atom[3]

When a photon with the right energy to excite the electron from level $1s$ to $2p$ enters the atom, the hyperfine levels are so close together that there is an equal possibility of the electron landing in any F level with any M. However, there are certain rules the electron has to follow, one of which is that the electron's M value cannot be altered by more than 1. This is to say, $\Delta M = -1, 0, 1$. ΔM is decided by the nature of the photon. When the applied magnetic field is parallel to the direction of propagation of the photon, a right-circularly-polarized photon will always give $\Delta M = 1$ and a left-circularly-polarized photon will give $\Delta M = -1$. The rule also applied to emission. For example, when the electron falls from $2p$ back to $1s$, ΔM is equally likely to be 1, 0, and -1, so the average $\Delta M = 0$.

In out experiment, a right-circularly-polarized laser beam with the right frequency to excite electrons from ground state to first excited state passes through some Rubidium vapor and is then detected by a photodiode. Because of the polarization of the photons, transitions induced all have $\Delta M = 1$. The average emissions have average $\Delta M = 0$, so very quickly all the electrons will be "pumped" up to the highest M level. When that happens, the Rubidium vapor is unable to absorb any more photon, which means that it has become transparent to the laser beam. Then an RF (Radio Frequency) signal is introduced into

the system. When the RF signal has the exact energy between the Zeeman splitting, it "depumps" the electrons from the highest M level down, and the Rubidium vapor can absorb photons again, which will cause a sudden decrease in the intensity of the laser beam detected by the photodiode.

II. EXPERIMENT

To implement the optical pumping process, we used the apparatus shown in Fig. 2, manufactured by TeachSpin Inc[1].

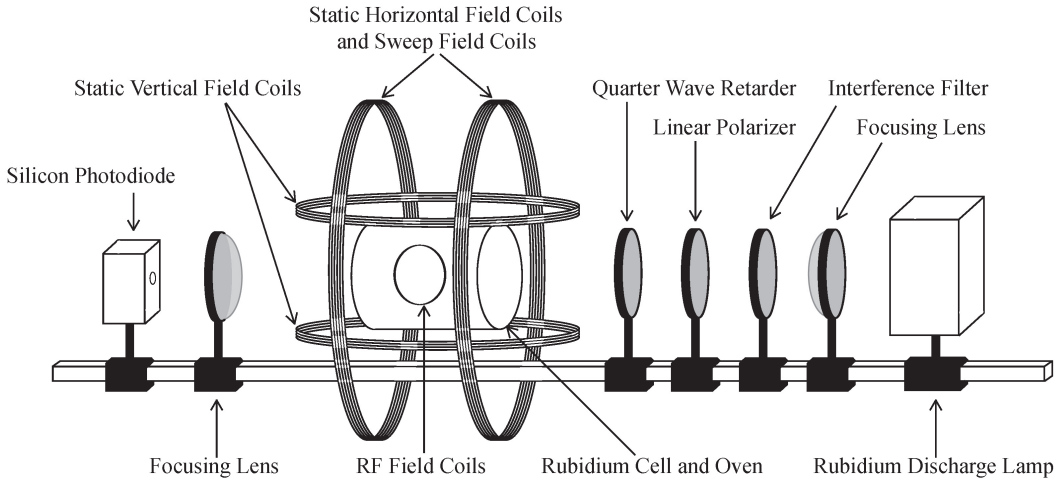

FIG. 2. Optical pumping of Rubidium apparatus including the labelled components[2]. There are three main components to this optical pumping set up on the optical rail. The light source (right hand side), the rubidium cell in the center (kept at 50°C) surrounded by Helmholtz and RF field coils (center) and the detector (left hand side).

Light is emitted from a rubidium lamp on the right side of the optical rail with a wavelength of 794.8 nm with an energy of 1.56 eV; the light itself is purple to the visible eye. the interference filter limits the bandwidth of light with a pass band of 790 nm to 830 nm, and the linear polarizer and quarter wave retarder convert the light from random polarization to

circular polarization. The circular polarized light mandates only $\Delta M = +1$ electric dipole transitions in the atom.

The circularly polarized photos next enter the temperature controlled (50°C) rubidium cell containing both isotopes of rubidium, ^{85}Rb and ^{87}Rb. The Helmholtz coils provide the magnetic fields, are driven by dial controlled variable voltage dividers, and are monitored by the x-axis input of the oscilloscope. The RF field coils are driven by a function generator and drive the sample out of the optically pumped state when the sweep field is at resonance.

The left side of the optical rail measures the intensity of light passing through the sample which in effect allows us to see when the sample is driven out of the optically pumped state. This signal detected by the photodiode is monitored by the y-axis input of the oscilloscope.

In the beginning of the experiment, we removed the quarter wave retarder and the linear polarizer to align the setup by moving the filters and focusing lenses so that the photodiode voltage reading is maximum. Then we put back two linear polarizers, one at either side of the cell, and aligned the two polarizers at 90° so that the photodiode voltage reads zero. The quarter wave retarded was then added back and rotated until the photodiode voltage reads a maximum value.

When there is zero field applied by the coils, we know the Earth's magnetic field will have an influence on the Zeeman splitting by allowing atoms to be pumped into the less absorbent stats. So to take into consideration this zero field, we first oriented the apparatus so that the light beam passing through the rubidium cell was aligned along the north-south axis to cancel out the local component of the Earth's magnetic field. The set of vertical Helmholtz coils were used to cancel the vertical component of the earth's field. Now all is left is the horizontal component of the Earth's magnetic field that will be in the opposite direction of the current in the horizontal Helmholtz coils (along the axis of the path of light).When the net field at the cell is zero (applied field and Earth's field are equal and opposite), the Zeeman levels become degenerate and we can no longer pump the atoms into less absorbing states, thus we see a district dip in the line of the oscilloscope in the y-axis connected to the photodiode.

III. RESULTS

A series of plots of photodiode voltage versus horizontal sweep voltage are obtained at different RF frequency.

The horizontal sweep voltage is translated into sweep magnetic field strength by

$$B_{\text{sweep}} = 8.991 \times 10^{-3} I N R_{coil}^{-1} \tag{5}$$

where

$$I = \frac{V_{\text{sweep}}/\text{Gain}}{R} \tag{6}$$

$N = 11$ is the number of wires wrapped on each side and$R_{coil} = 0.1639m$ is the average radius of the loop. Gain is 1 in this experiment and R is the recorder output resistance, which is 30Ω. This was calculated by taking the voltage across the sense resistor labeled "recorder output" on the horizontal magnetic field sweep on the optical pumping instrument and was 30 times larger than the monitor voltage which has a sensor resistance of 1Ω. Using Ohm's law of $V = IR$, we know that the resistance of the recorder output is 30 times that of the monitor, hence 30Ω.

Fig. 3 shows two of the plots after the horizontal sweep voltage is converted to magnetic field strength. The first dip is where zero field transition happens, the first dip is where the ^{87}Rb transition happens and the second dip is the ^{85}Rb transition. The difference between the zero field transition and the Rb transition is calculated to find the true magnetic field that is resonant with a given RF frequency. The resonant magnetic field is found for both ^{87}Rb and ^{85}Rb at RF frequency varying from 10kHz to 100kHz with a step size of 10kHz, and is also plotted versus the RF frequencies.

I suggest putting Fig 5 ahead of the tables, since otherwise it is too far away from the discussion of the figure in the text, and the data tables are just for reference information. Table.I in the appendix shows the positions of the dips and the resonant fields with uncertainties. Fig. 4 shows the plot, from which it can be seen that resonant magnetic field

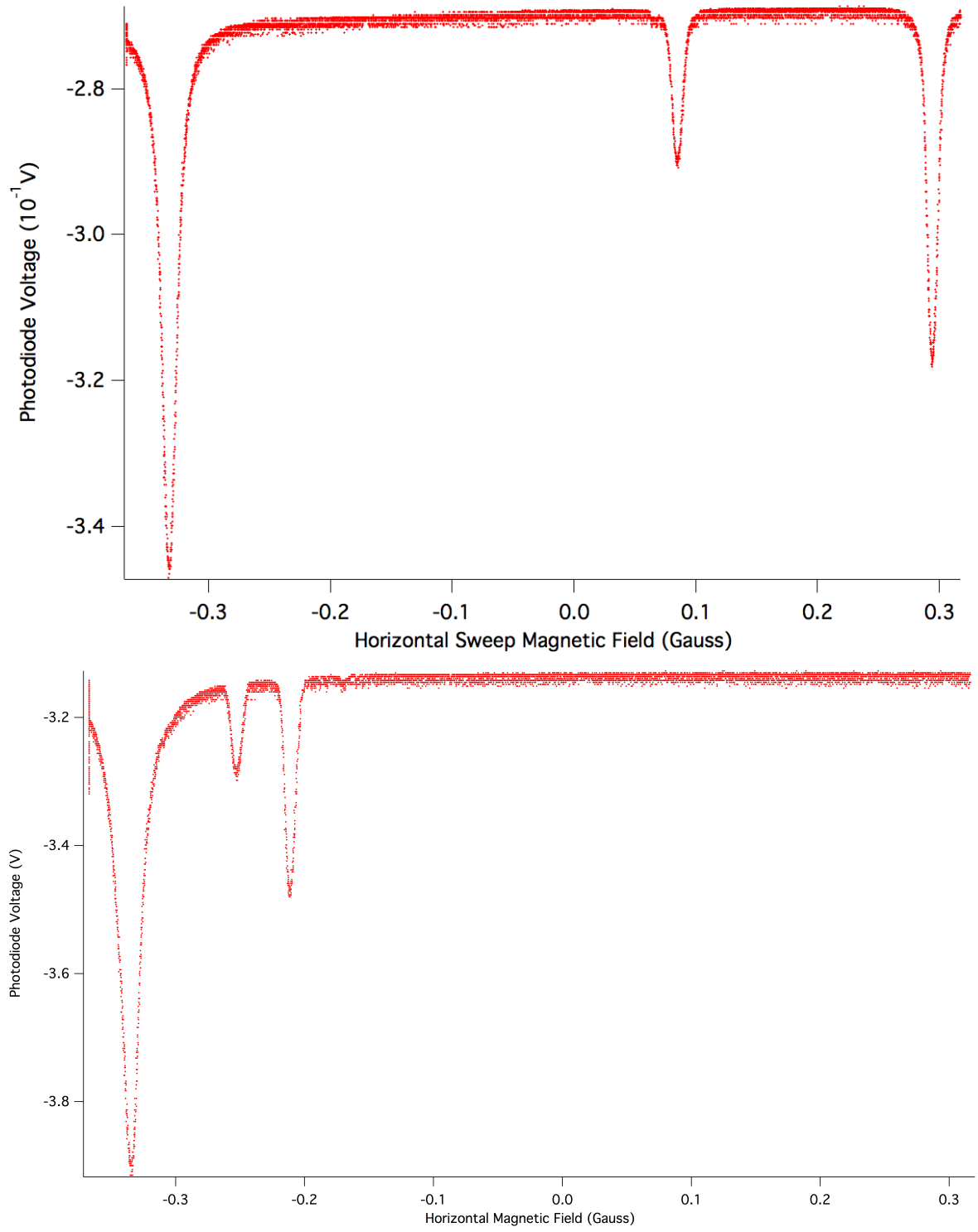

FIG. 3. Photodiode voltage versus magnetic field strength at 100 kHz (top) and 20kHz (bottom). The left trough is the zero field resonance, the middle trough is RF absorption for ^{87}Rb and the right trough is for ^{85}Rb.

and RF frequencies have a linear relationship. The different depth of the dips are caused by different amount of ^{87}Rb and ^{85}Rb in nature. There is more ^{85}Rb than ^{87}Rb, so the second dip is deeper. However, the photodiode voltage is not necessary for calculation in this experiment as we only cared about the location of the dip on the x-axis.

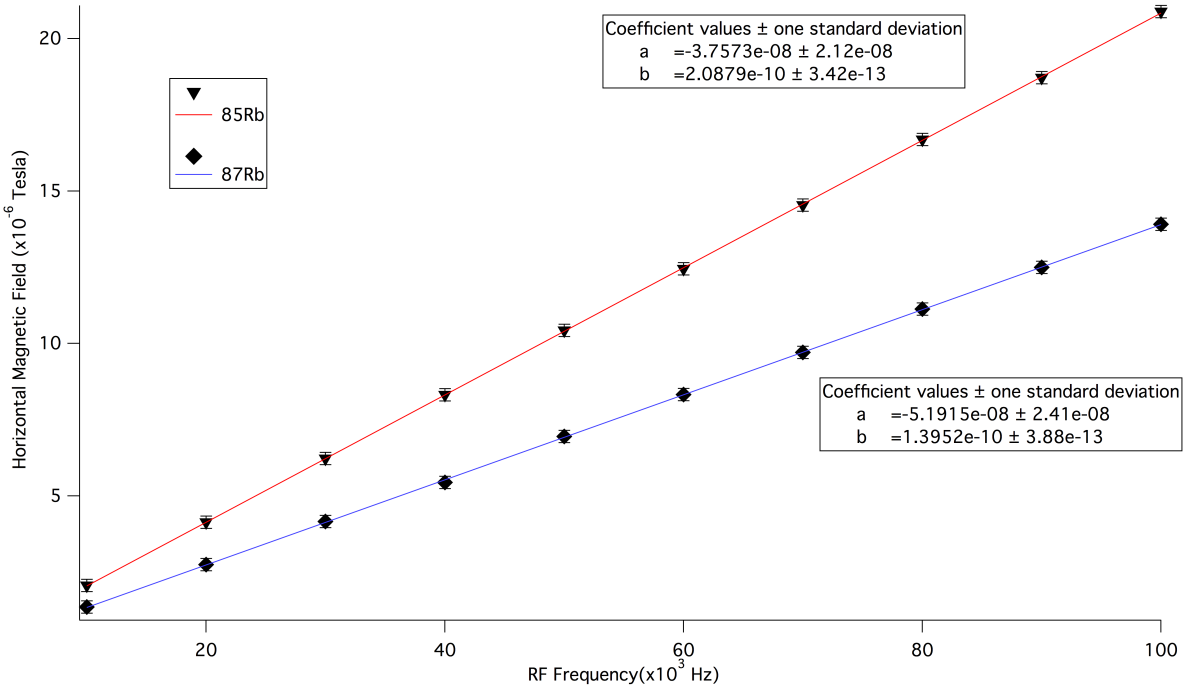

FIG. 4. Horizontal magnetic field strength in resonance vs. RF frequency. you should include a short explanation of the meaning of the slope, such as how it is related to g. linearly proportional? inversely proportional?

The ^{87}Rb and ^{85}Rb scatter plots are separately fitted by lines. The slope of the ^{87}Rb is $4.1856 \times 10^{-10} \pm 1.16 \times 10^{-12}$ and the slope of the ^{85}Rb is $6.2637 \times 10^{-10} \pm 1.03 \times 10^{-12}$. Resonance only occurs when the RF signal has the right energy to depump the electrons. The "right" energy here is the Zeeman energy, which is the difference in energy between two neighbor M levels.

The energy of the RF signal is given by

$$E_{RF} = h\nu \tag{7}$$

Let $E_{RF} = E_z$ in Eq. 1 and move the terms around, we get

$$B = \frac{h}{g_F \mu_0} \nu \tag{8}$$

where B is the the resonant magnetic field and ν is the RF frequency. And it is easy to see that they have a linear relationship. g_F can be calculate from the slope of the fit line:

$$g_F = \frac{\mu_0}{h} \times \frac{1}{\text{Slope}} \tag{9}$$

g_F is found to be 0.1708 ± 0.0004 for ^{87}Rb and 0.1141 ± 0.0002 for ^{85}Rb where the expected values are $1/2$ and $1/3$.

IV. DISCUSSION

V. CONCLUSION

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VI. APPENDIX

TABLE I. Optical pumping resonance field data

RF (kHz)	Zero Field Dip (Gauss)	Rb87 Dip (Gauss)	Rb85 Dip (Gauss)
100	-0.33216±2.40E-05	0.08509±1.80E-05	0.29449±1.44E-05
90	-0.33221±2.37E-05	0.042623±2.09E-05	0.22929±1.61E-05
80	-0.33336±2.79E-05	0.00052957±1.90E-05	0.16733±1.23E-05
70	-0.33167±3.33E-05	-0.040531±2.51E-05	0.10456±1.51E-05
60	-0.33178±2.96E-05	-0.082066±2.36E-05	0.041789±1.62E-05
50	-0.33256±3.65E-05	-0.12408±2.52E-05	-0.019752±1.86E-05
40	-0.33227±3.11E-05	-0.16902±3.25E-05	-0.082741±2.29E-05
30	-0.33257±3.25E-05	-0.20774±3.69E-05	-0.1458±2.44E-05
20	-0.33519±3.26E-05	-0.2527±3.73E-05	-0.2111±2.93E-05
10	-0.335555±3.79E-05	-0.29493±7.74E-05	-0.27365±3.03E-05

TABLE II. Optical pumping resonance field data (continued)

RF (kHz)	RB87 Resonant Field (10^{-6}Tesla)	RB85 Resonant Field (10^{-6}Tesla)
100	13.908±1.28E-03	20.8883±1.4E-03
90	12.4944±1.33E-03	18.7167±1.49E-03
80	11.1297±1.34E-03	16.6897±1.56E-03
70	9.7046±1.61E-03	14.541±1.95E-03
60	8.3238±1.53E-03	12.4523±1.77E-03
50	6.9493±1.84E-03	10.4269±2.06E-03
40	5.4417±1.8E-03	8.3176±2.12E-03
30	4.161±1.90E-03	6.2257±2.31E-03
20	2.7497±2.06E-03	4.1363±2.33E-03
10	1.3542±2.27E-03	2.0635±3.84E-03

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[1] TeachSpin Instructions Manual, *Optical Pumping of Rubidium OP1-A*, 6/2002.

[2] Welcome to the University of Minnesota Methods of Experimental Physics Laboratory, http://spa-mxpweb.spa.umn.edu/s11/Projects/S11_OpticalPumping/apparatus.html, *Optical Pumping of Rubidium.*

[3] Optical Pumping, http://internal.physics.uwa.edu.au/ stamps/2006Y3Lab/SteveAndBlake/theoretical.html