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Abstract

Optical pumping is an important technique that allows for the manipulation of atomic and molecular energy levels using light. In this report, we present the results of an optical pumping experiment performed on rubidium atoms. Our goal was to study the hyperfine structure of rubidium atoms and to measure the Zeeman splitting of the energy levels.

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1 Introduction

1.1 Calculate L, I, J, F for two isotopes

Rubidium naturally occurs as a mixture of two isotopes: 72.2% of ^{85}Rb and 27.8% of ^{87}Rb. The Rb atom contains three forms of angular momentum: electron orbital angular momentum L, electron spin S, and nuclear spin I. Out of the 37 electrons of Rubidium, 36 electrons fully occupy their energy shells and one valence electron is responsible for the electron orbital angular momentum. So, L = 0 for the 5s ground state , while L = 1 for the 5p excited state. The electron spin in both states is S = 1/2. The nuclear spins are: I = 5/2 for ^{85}Rb, and I = 3/2 for ^{87}Rb.

Fine structure is the energy splitting caused by relativistic effects that couple the electronic orbital angular momentum to its spin. The total electronic angular momentum J follows $|\boldsymbol{L}-\boldsymbol{S}| \leq \boldsymbol{J} \leq \boldsymbol{L}+\boldsymbol{S}$. The 5p electronic excited state splits into $^2P_{1/2}$ state and $^2P_{3/2}$ state. Superscript is 2S+1 and subscript is J. There is no fine-structure splitting of the 5s electronic ground state because there is no electronic orbital angular momentum.

The hyperfine structure comes when we consider interactions between the total electronic angular momentum and the nuclear spin. We denote the total angular momentum F, $|\boldsymbol{J}-\boldsymbol{I}| \leq \boldsymbol{F} \leq \boldsymbol{J}+\boldsymbol{I}$. The hyperfine structure in the P-states is smaller than in the S-states because interaction between the electron and the nucleus is stronger in the S-states.

1.2 Explain Hamiltonian , Lande g factor

We consider the effect of the hyperfine Hamiltonian:

$$H_{hfs} = -\mu_I \cdot (B_J + B_{ext}) - \mu_J \cdot B_{ext} \tag{1}$$

where μ_I and μ_J are magnetic moments of the electrons and nucleus. The atomic electrons and the nucleus are gyromagnets, so their magnetic moment is proportional to their angular momentum:

$$\mu_I = g_I \mu_N I \quad , \quad \mu_J = g_J \mu_B J \tag{2}$$

where g_I and g_J are the *Landé* g-factor; μ_N is the nuclear magneton and μ_J is the Bohr magneton:(e is the electron charge, m_e is the mass of electron, and m_p is the mass of proton)

$$\mu_N = \frac{e\hbar}{2m_p} \quad , \quad \mu_B = \frac{e\hbar}{2m_e} \tag{3}$$

Looking at the H_{hfs}, we can separate it into an intrinsic term and an extrinsic term. $(\mu_I \cdot B_J) \equiv AhI \cdot J$ this term quantifies the energy of the nuclear magnetic dipole when placed

within the internal magnetic field. A is some constant that differ for the two isotopes and for the ground and excited states, provided in [1]. $-(\mu_I + \mu_I) \cdot B_{ext}$ this term describes the energies of the atomic magnetic dipoles placed within an externally applied magnetic field B_{ext}. Putting all the quantities above together, we get

$$H_{hfs} = AhI \cdot J - (g_I \frac{e\hbar}{2m_p} I + g_J \frac{e\hbar}{2m_e} J) \cdot B_{ext} \tag{4}$$

Landé g-factor can be calculated:

$$\begin{aligned} g_J &\simeq 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \\ g_F &= g_J \frac{F(F+1) - I(I+1) + J(J+1)}{2F(F+1)} \end{aligned} \tag{5}$$

As shown in Appendix A, the sign of g_F determines the order of energy levels in Zeeman structure. If g_F is negative, the highest m_F will be negative; if g_F is positive, the highest m_F will be positive.

The result of diagonalizing the Hamiltonian is known as the Breit-Rabi formula:

$$\frac{\nu}{B_{ext}} = \frac{2.799}{2I+1} \, [\frac{MHz}{G}] \tag{6}$$

$$\frac{\nu}{B_i + B_{ambient}} = \frac{2.799}{2I+1} \, [\frac{MHz}{G}] \tag{7}$$

B_{ext} is a combination of the ambient magnetic field in the laboratory and the magentic field caused by Helmholtz coils which is proportional to current. $B_i = ki$. Rearranging the equation:

$$\nu = (\frac{2.799}{2I+1} k) i + (\frac{2.799}{2I+1} B_{ambient}) \tag{8}$$

1.3 Optical pumping

In this experiment, our goal is to induce and observe the effects of Zeeman transitions on the electronic ground states of rubidium atoms. Zeeman structure is induced with an external magnetic field. The energy state is characterized by magnetic quantum number m_F which ranges $\{-F, ..., F\}$. The electric dipole selection rules dictate that $\Delta m_F = +1$ for absorption of light and $\Delta m_F = 0, \pm 1$ for emission of light. Though spontaneous emissions lower m_F, atoms will all reach a high m_F state after many cycles of optical pumping. This state is known as the "pumped state" or the "dark state" because atoms no longer absorb light, as dictated by the selection rules. If we now introduce a radio-frequency magnetic field to the atom, we can lower the m_F energy level and bring atoms away from "pumped state".

This technique is known as "optically detected magnetic resonance" (ODMR). Reference [2] provides an excellent illustration of this process. Through careful calibration, we can find the resonant frequency that change m_F by 1 and study the energy level between zeeman transition.

2 Experimental Procedures

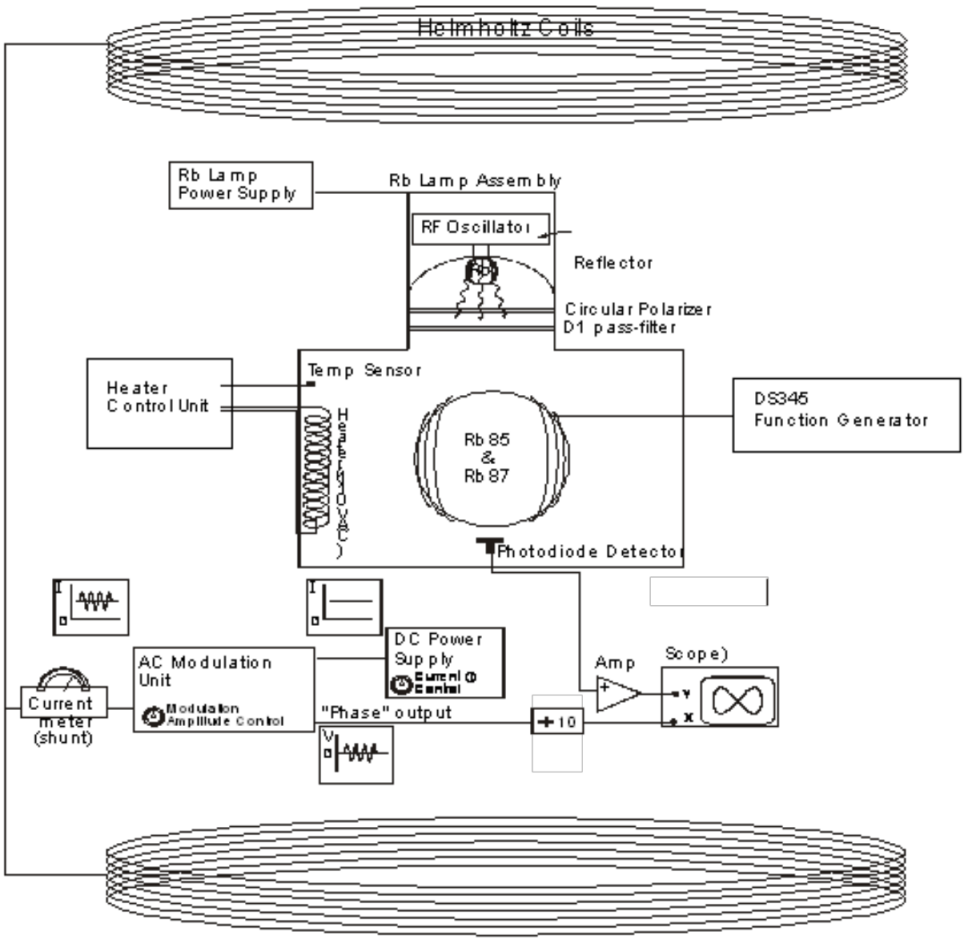

Figure 1: Schematic drawing for the experiment

2.1 Equipment setup

A schematic drawing is shown in Figure 1.

- Rubidium gas bulb: There are low-density buffer gas and small amount of rubidium. At low temperatures, most of the rubidium resides on the walls of the glass cell. However,

as the bulb is heated, some of the rubidium is released into the buffer gas inside the optical bulb. By adjusting the temperature of the bulb, the density of rubidium in the buffer gas can be controlled. Buffer gas is used to greatly increase the time required for an alkali atom to diffuse back into the wall of the bulb. The heater produces a stray magnetic field that causes interference in our ODMR measurements. To ensure high measurement precision, we opt to turn off the heater during the measurements.

- Rb lamp and Optical filters: Optical pumping light source comes from a lamp that contains rubidium gas within an electronic discharge. The Rb lamp ensures that its emissions can drive all of the D1 and D2 lines for both isotopes of rubidium. Next, light passes through an optical polarizer that selectively transmits only circularly polarized light. This polarization set the selection rules for absorption and emission of light. Subsequently, the light passes through a "D1 pass filter", which is an interferometric filter that allows the transmission of light only if its wavelength is approximately 795 nm(D1 transition). This is because atoms will only reach pumped state/dark state in D1 transition.

- Detector and amplifier: Source light pass through optical filters and then gas bulb and eventually hitting a photodiode detector. The current signal is amplified by a SR560 Amplifier and sent to an oscilloscope.

- Radio-frequency coil: The glass bulb is positioned between two coils connected in series. The SRS DS345 function generator powers the coils that produce a radio-frequency magnetic field.

- Light-proof box: The gas bulb, optical filters, heater, rf coil are all located inside of a light-proof and thermally-insulated box. The purpose of this box is to prevent interference from room light and maintain a constant temperature over an extended time.

- Helmholtz coil: Two large, coaxial, circular coils are positioned outside the light-proof box to generate magnetic fields along the z axis. The Helmholtz coils are powered by a current source that comprises a dedicated DC current supply and an AC current. These coils are arranged in the Helmholtz configuration, where the selection of the separation d and radius a ensures that the magnetic field is nearly constant. Neglecting the wire thickness, so that all the wire in each coils has the exact radius a and separation d between coils, the axial magnetic field at the center(z=0) is given as

$$0.9 \times 10^{-2} \frac{Ni}{a} \ [\frac{G\ m}{A}] \tag{9}$$

2.2 Finding ODMR

Using Equation 9, with i = 1 A current, N = 135 turns in each coil, and coil radius of a = 27.5 cm, the field generated is 4.41413 G. Using Equation 7, the expected zeeman transition frequencies are 2.0592 MHz for ^{85}Rb and 3.0888 MHz for ^{87}Rb when neglecting ambient field.

Begin by heating the gas bulb to approximately 50 $°C$. Start with a DC current of 1 A flowing through the Helmholtz coil. Configure the DS345 unit to generate a sinusoidal current with a linearly swept frequency over a 3 MHz range that covers the expected resonance frequencies, using a sweep period of 100 ms. Set the peak-to-peak output voltage to 5 V.

To measure the amplified photodiode signal as a function of the frequency of the rf magnetic field. We connect the "Modulation Output" of the SRS DS345 unit to the X-axis (Channel 1) and display the photodiode signal on the Y-axis (Channel 2). The signal is shown in Figure 2. Each peak represents the resonant frequency(ODMR) for an isotope. Since the first peak is bigger than the second peak, the first peak corresponds to the more abundant isotope ^{85}Rb, while the second peak corresponds to the less abundant isotope ^{87}Rb.

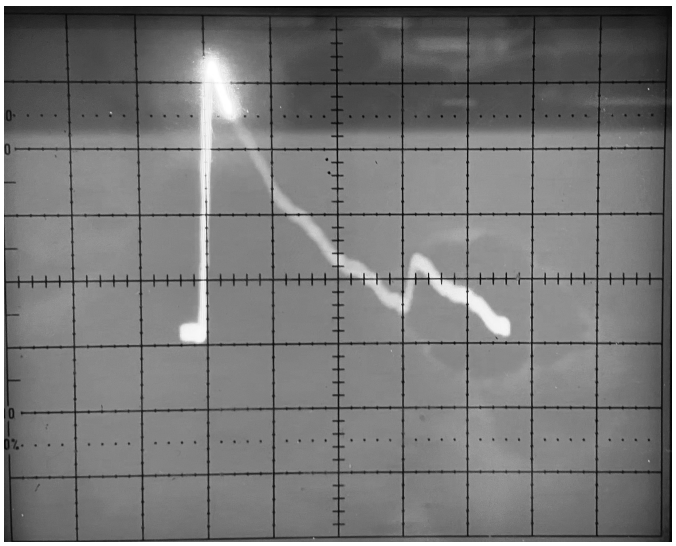

Figure 2: Amplified photo diode signal with large span frequency modulation

2.3 Finding good settings for the bulb temperature

To find the temperature that gives the most signal, we raise the temperature to 50 °C and record the changes in signal as temperature gradually drop to 30 °C. As shown in Figure3, the optimal temperature for our setting is 44 °C. The error for the signal is 0.1 since 0.2 is the smallest reading increment of the signal.

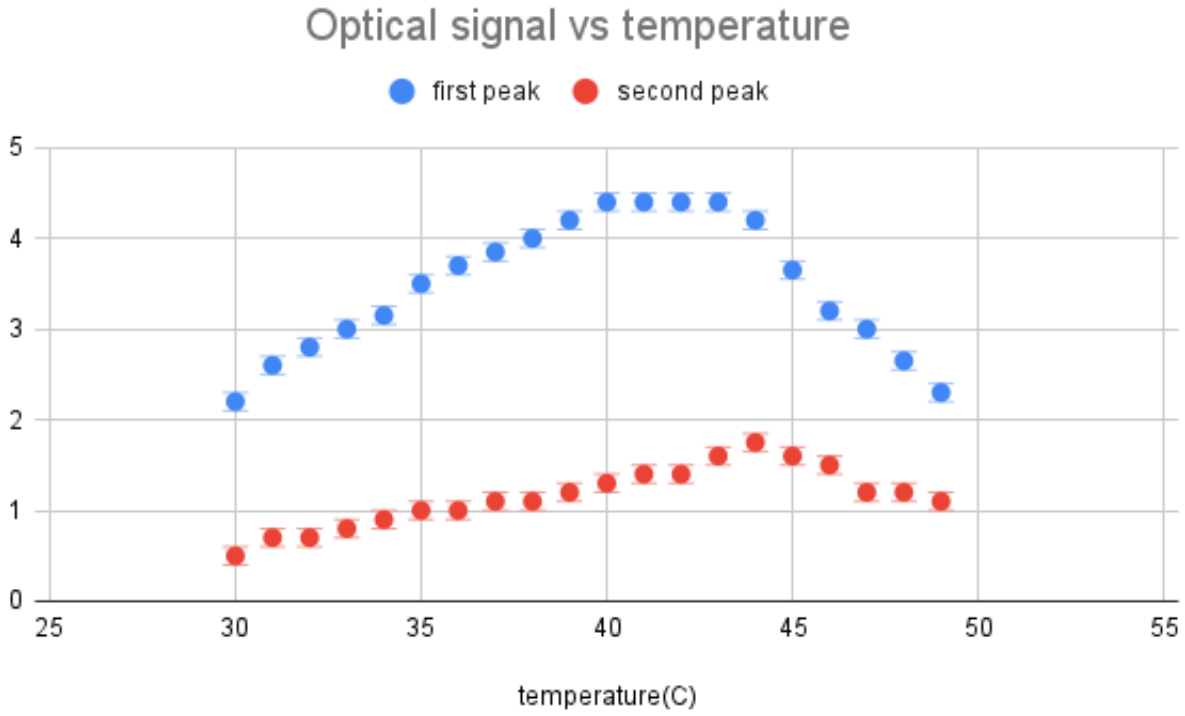

Figure 3: Optical signal amplitude vs. Temperature for both isotopes

2.4 Current modulation/lock-in detection of the resonance frequency

2.4.1 resonance frequency vs. current data scan

Lock-in detection applies a high-frequency modulation to the experimental apparatus and then measures the variation of a signal at the modulation frequency. For the purpose of error analysis, we should keep a constant modulation amplitude.

To implement this method, we activate the field modulation by flipping the "Field" switch and the "Phase Out" output by toggling the "Phase Switch." We connect the Phase Out signal to the X-axis(Channel 1) of the oscilloscope and connect amplified photodiode voltage to Y-axis(Channel 2). The phase out signal tracks the variation of modulation signal. This technique allows us to accurately find the resonant frequency. To determine the resonant frequency for each isotope, we vary the rf frequency until we observe a symmetrical Lissajous figure in the signal. Once we have identified the resonant frequency for one isotope, we adjust the rf frequency to find the resonant frequency for the other isotope.

2.4.2 Zeeman resonance frequency at zero DC current

We proceed to measure the Zeeman resonance frequency in the absence of any DC current or RF field, with the only remaining external field being the ambient magnetic field in the laboratory.

In the absence of an applied magnetic field, the magnetic dipole moment of the atom interacts with the ambient magnetic field resulting in a shift of the energy levels of the atom. This shift in energy levels leads to a resonance feature in the measured signal when the applied field is precisely zero and the Helmholtz field exactly cancels the ambient field along the optical axis.

2.5 Timescales for optical pumping using square wave amplitude modulation of the rf field

We want to measure the times of optical pumping and of Zeeman transitions. We recall the previous settings for a strong Zeeman resonance. Then, set the rf-generator to produce an amplitude modulated sinusoidal signal with a square wave modulation at a low frequency (e.g., a few Hz) and a sinusoidal signal at the previously determined strong Zeeman resonance frequency. Use the oscilloscope to observe the time-trace of the amplified photodiode signal.

When the Helmholtz field exactly cancels the ambient field along the optical axis, current is 0.08A. Using Equation 9, we calculate the ambient magnetic field to be 0.2471 Gauss.

3 Results and Analysis

In Figure 4, at zero current the resonant frequency is due to ambient magnetic field. Using chi square fit, we find the fits for ^{85}Rb and ^{87}Rb. The error for the frequency is set within the range which resonant signal is maintained experimentally. The upper and lower range of each resonant signal is in Appendix B.

Table 1: Chi-square fit for Frequency vs. current plot

	slope	y-intercept	Chi-Square	Degrees of Freedom
^{85}Rb	2.029	-0.197	0.001	19
^{87}Rb	3.042	-0.302	0.000	13

To determine nuclear spin for two isotopes, we use the fit data and Equation 8. Plugging the magnetic field of Helmholtz coils given by Equation 9 into Equation 8. We equate the slope of each plot with the slope in Equation 8. We find I_{85} to be 1.5326 and I_{87} to be 2.5474. Our results differ by 2.2% and 1.8% respectively from the known values, 3/2 for I_{85} and 5/2 for I_{85}. The discrepancy may be due to our assumption of perfect Helmholtz coils, as we

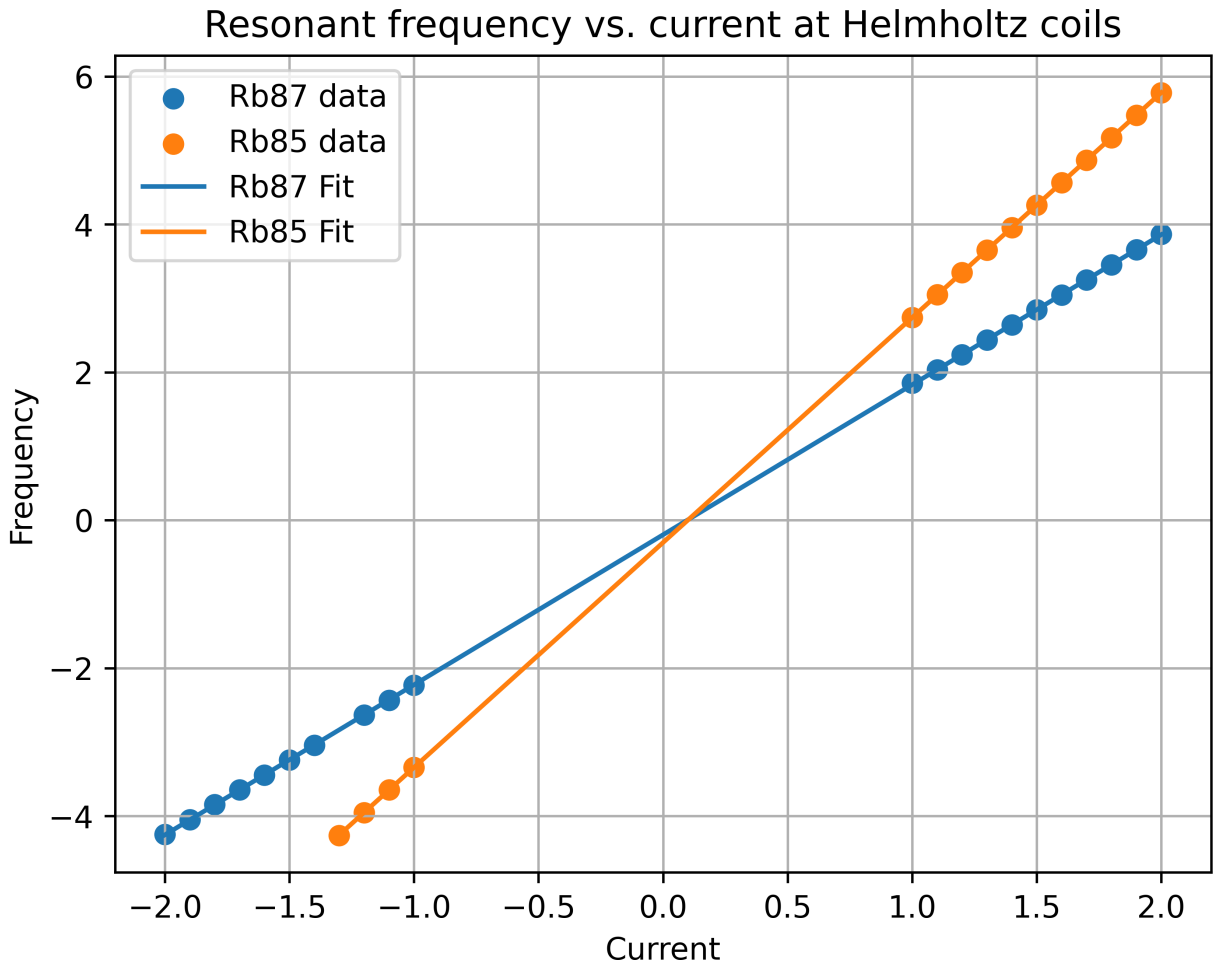

Figure 4: Resonant frequency vs. current applied at Helmholtz coils

neglected factors such as the thickness of the coils and the variations in the distance from the center to each coil. While we assume that the magnetic field generated by the Helmholtz coils acts at the center of the gas bulb (z=0), it's important to note that the field actually vary slightly at different z positions.

To determine the ambient magnetic field, we plug the y-intercept as ν in Equation 8. We get 0.428 Gauss for ^{85}Rb 0.4386 Gauss for ^{87}Rb.

In the absence of a magnetic field, the energy levels of the atoms or molecules are not split, and there are no separate energy sub-levels. However, the natural frequency of the transition is still present, and if the source lamp frequency matches this frequency, there can be a resonance.

We find the "pumping time" (1/e) for the non-pumped gas to become optically pumped and the "relaxation time" for the rf-driven gas to arrive at its new steady state. At a current of 1A and an rf frequency of 2.29MHz, we have determined that the pumping time for ^{87}Rb is

63.1 ±4 ms, and the relaxation time is 100 ±4 ms. At a current of 1A and an rf frequency of 3.448MHz, we have determined that the pumping time for ^{87}Rb is 76.9 ±4 ms, and the relaxation time is 98.5 ±4 ms. The error for the time is 4 since 8 is the smallest reading increment of the time signal.

4 Conclusion

We observed the Zeeman effect, where the energy levels of the atoms split in the presence of a magnetic field. By adjusting the strength of the magnetic field, we were able to determine the resonance frequency at which the atoms would absorb the incident light. A more detailed analysis in external magnetic field could be beneficial for demonstrating the effectiveness of the optical pumping technique in creating population inversion in atoms.

References

(1) Steck, D. Rubidium 85 D line data, Rubidium 87 D line data. *h ttp://steck. us/alkalidata* **2008**.

(2) Bloom, A. L. Optical pumping. *Scientific American* **1960**, *203*, 72–81.

A Energy diagrams for Rubidium

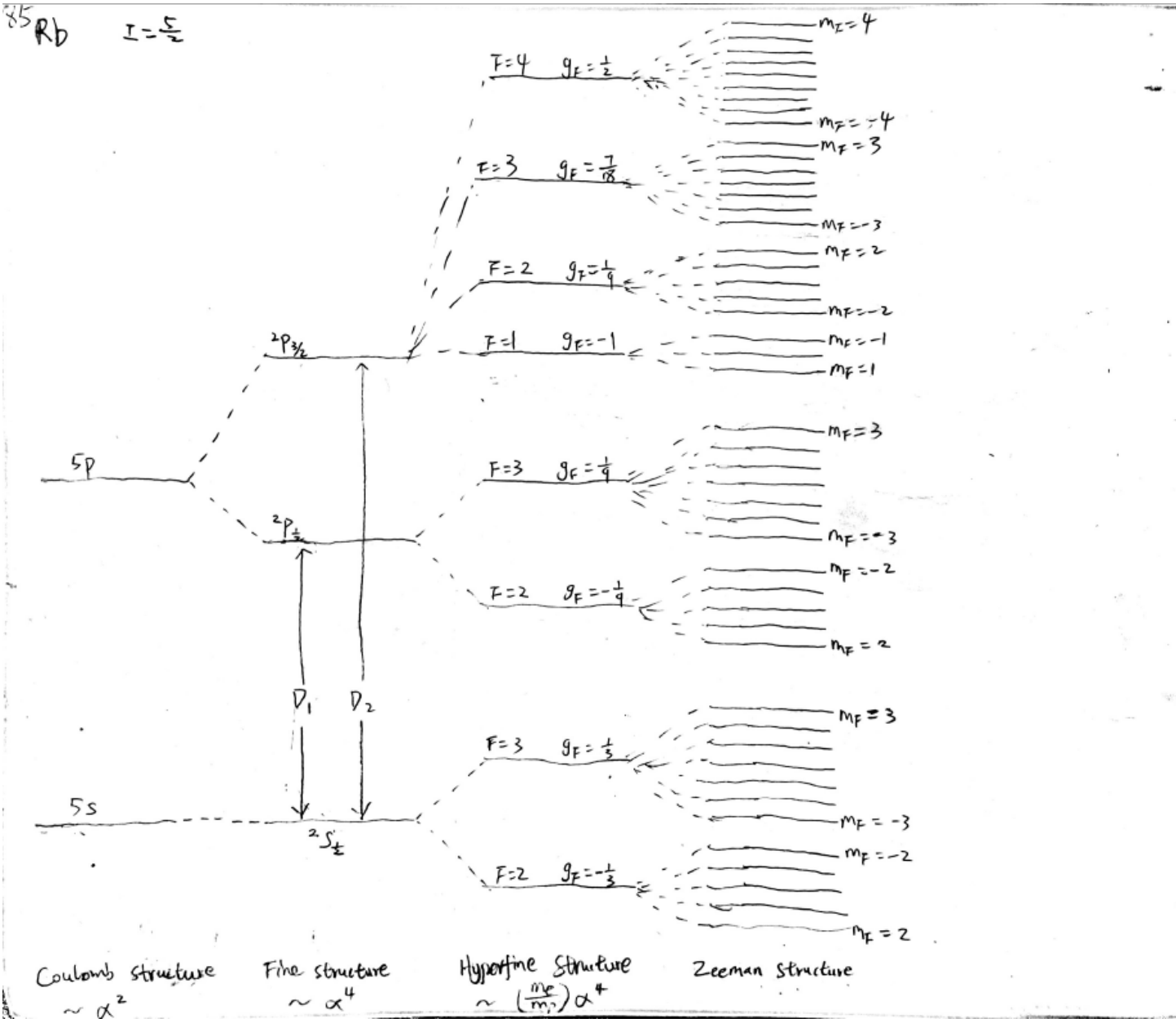

Figure 5: ^{85}Rb energy diagrams

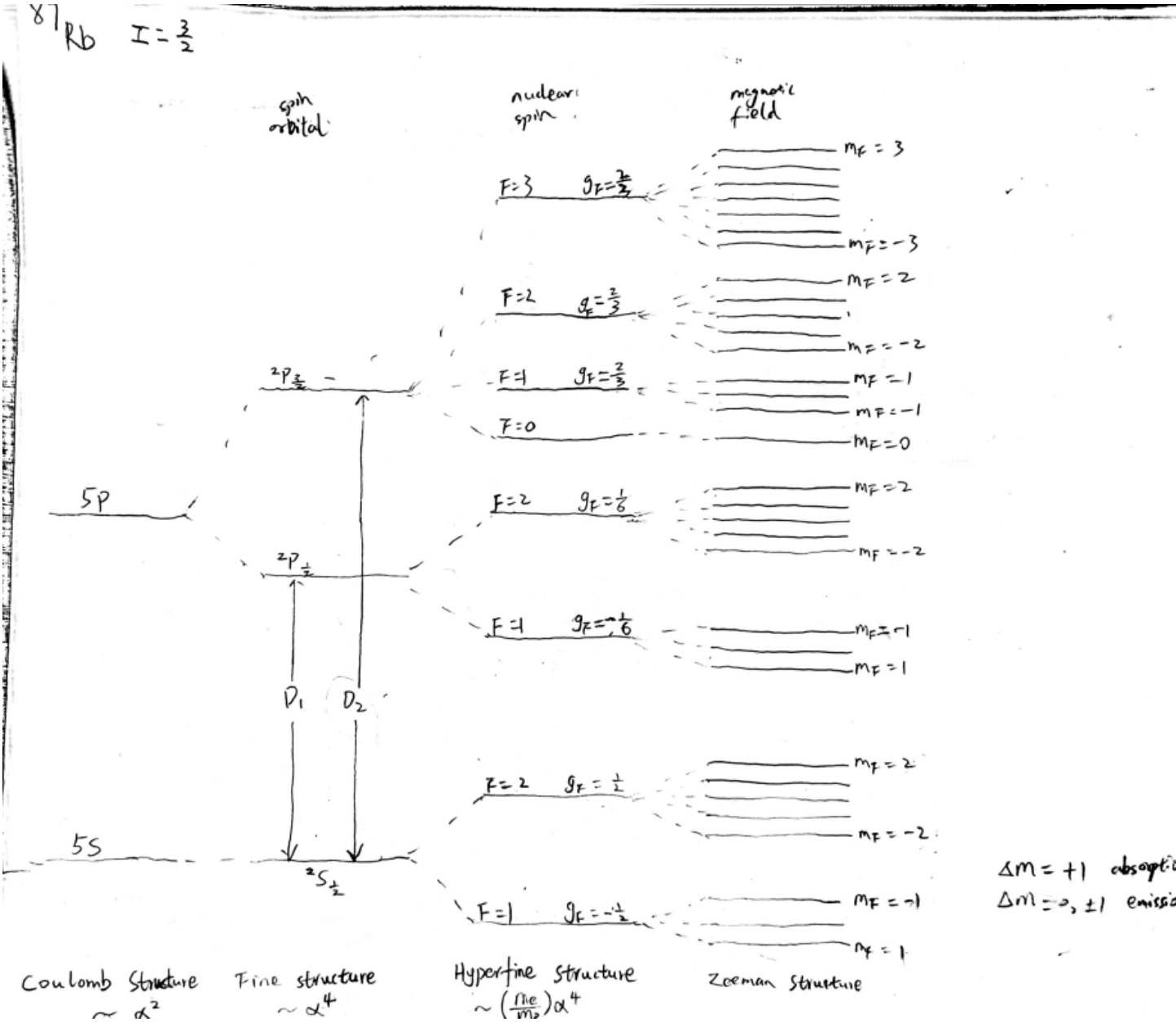

Figure 6: ^{87}Rb energy diagrams

B Raw data

Table 2: Data for Frequency vs. current plot

current (A)	frequency (MHz)	lower range (MHz)	upper range (MHz)
-2	-4.248	0.014	0.015
-1.9	-4.05	0.012	0.002
-1.8	-3.847	0.007	0.005
-1.7	-3.645	0	0.007
-1.6	-3.4464	0.003	0.003
-1.5	-3.2434	0.0039	0.0012
-1.4	-3.041	0.0042	0.003
-1.2	-2.6368	0.0007	0.0015
-1.1	-2.4354	0.0003	0.0007
-1	-2.2336	0.0005	0.001
1	1.855	0.0012	0.0006
1.1	2.0357	0.0004	0.0011
1.2	2.2361	0.0004	0.0006
1.3	2.4388	0.0004	0.0007
1.4	2.6419	0.1803	0.0011
1.5	2.8444	0.0006	0.0008
1.6	3.0466	0.001	0.0008
1.7	3.2499	0.0008	0.0014
1.8	3.4543	0.0012	0.0011
1.9	3.6589	0.0011	0.0011
2	3.865	0.0016	0.0012
current (A)	frequency (MHz)	lower range (MHz)	upper range (MHz)
-1.3	-4.2617	0.0038	0.0062
-1.2	-3.954	0.004	0.007
-1.1	-3.647	0.001	0.003
-1	-3.3435	0.0005	0.003
1	2.7427	0.0004	0.0013
1.1	3.0509	0.0009	0.0016
1.2	3.3509	0.0007	0.0012
1.3	3.6544	0.0007	0.0014
1.4	3.9583	0.0013	0.0022
1.5	4.2593	0.001	0.002
1.6	4.5644	0.0017	0.0026
1.7	4.8694	0.0013	0.0029
1.8	5.173	0.0028	0.0052
1.9	5.4754	0.003	0.005
2	5.7804	0.002	0.006