

Chapter 1

Optical Pumping

1.1 Introduction.

This optical pumping lab might be considered a "Course" in Atomic Physics with the topics:

- Optical Pumping of Rubidium Atoms, ^{85}Rb and ^{87}Rb
- Explore Magnetic Hyperfine Interactions of Rubidium
- Observe Zero-Field Transitions
- Confirm Breit-Rabi Equation
- Observe Double Quantum Transitions
- Study Rabi Oscillations
- Measure Optical Pumping Times
- Study Temperature Dependence of Atomic Parameters

You should do as many of the experiments as time allows.

In optical pumping circularly polarized photons are generated, sent through an absorbing gas, and then to a detector. See Fig. 1.1

Right circular polarized photons carry one unit of angular momentum. To understand the nature of optical pumping suppose the absorbing atoms can be represented by the simple spin system shown in Fig. 1.2. Absorbed photons will take the absorbing atom from the $M=-1$, ground state to the excited state, which then decays equally to all three M states of the ground state. Since there is no path to take the $M=0$, and $M=+1$ ground states back to the $M=-1$ state, the state which becomes depleted. The depletion of the $M=-1$ state as a function of time is shown in Fig. 1.3. Since absorption can only take place for the $M=-1$ state, the gas of absorbing atoms becomes more transparent and allows more

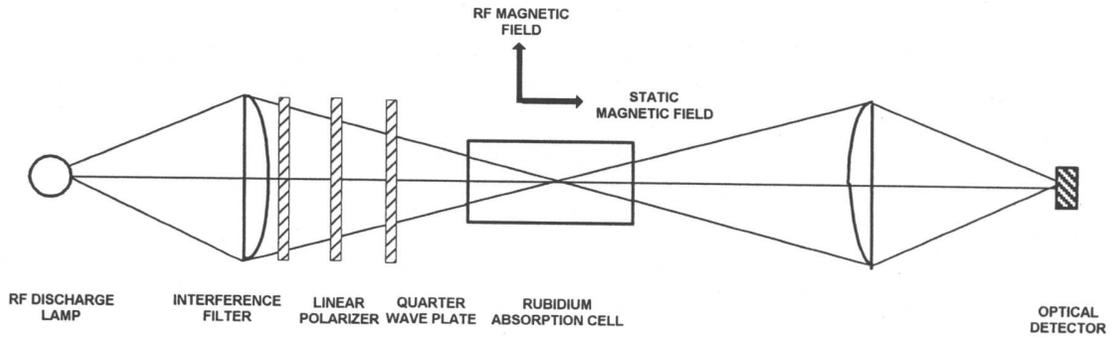


Figure 1.1: Apparatus arrangement for optical pumping.

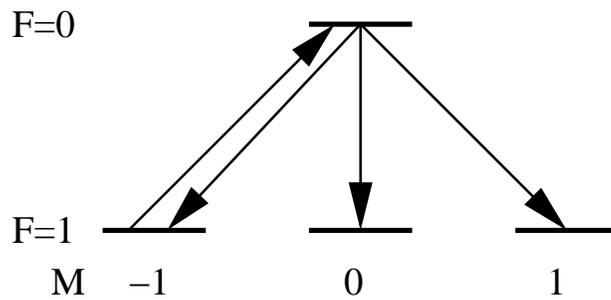


Figure 1.2: A simple spin system for which the ground state has total angular momentum 1, and the excited state has total spin 0. The excitation by right circular light is shown as are the three decay modes of the excited state.

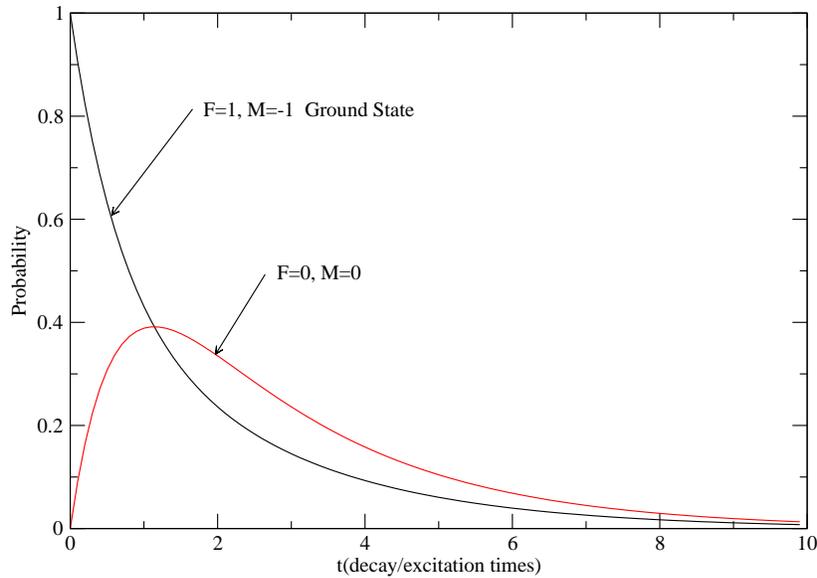


Figure 1.3: The time dependence of the populations of the ground state and excited state. It is assumed that the rate of excitation from the ground state equals the rate of decay from the excited state.

Isotope	Nat.Abund.(%)	I	μ/μ_N	J	F(lower)	F(higher)
^{85}Rb	72.17	5/2	1.35303	1/2	2	3
^{87}Rb	27.83	3/2	2.75124	1/2	1	3

Table 1.1: Properties of the Rb isotopes.

light to reach the detector; this increase of light transmission is the signature of optical pumping.

The actual system that you will be studying is Rb. Some of the characteristics of Rb are in Table 1.1. While this is clearly more complicated than the simple case of Fig. 1.2, for right circular light the result is nearly as simple. The maximum M state for both isotopes will become much more heavily populated. See, e.g., Franzen and Emslie[?] and the discussion in the TeachSpin Manual.

To determine that the system has been optically pumped one needs to find a means of de-pumping the maximum M state. Upon being de-pumped the gas will absorb more readily and less light will be detected. One means of de-pumping is to arrange that the magnetic field which is applied goes to zero. Then M is no longer a good quantum number and collisions can easily change the orientation of the atom. A second means to de-pump is to induce by an RF magnetic field, transitions from the maximum M state.

Note: If you quantize along the photon's propagation axis, but apply a magnetic field opposite to that direction, then the energies of the M levels will be inverted. Or,

conversely, if you quantize along the positive field direction, then the angular momentum of the photon is reversed and the maximally populated state will have the most negative value.

1.2 Setting up the Optical Pumping Apparatus

To connect the electronics of the device, first plug the Lamp power into the back panel connector. Then plug the blue Thermocouple into lower front panel and blue heater banana plugs. Next, plug Black plastic Pre-amp power and Detector BNC into lower front panel. Plug in Vertical Field banana plugs into lower front panel. Finally plug in the Horizontal Sweep Field banana plugs into the lower front panel. Now, turn on the power switch on the back panel entry module. The temperature regulator will display the current cell temperature. **Check that the set point of the regulator is 50°C.** Push the scroll key twice. **SP** will be displayed for 1.5 seconds and then the value of the set point will be displayed. If the value is not 50°C, push the up or down keys till it is. Push the scroll key again twice. **PROC** will be displayed for 1.5 seconds and then the current temperature. After these settings, the lamp will take a few minutes to warm up. Usually, it takes 10-20 minutes for the cell oven to stabilize. To obtain maximum optical alignment, the room lights are recommended to be off for the alignment. Set the preamp gain for 10MΩ. On the detector amplifier set the gain = 1, gain mult. = x1, time constant = 100ms, meter multiplier = x1, and DC Offset = 0. Use a card to block the lamp and make sure this signal is from the lamp and not the room lights. If the signal is off scale. change the meter multiplier to x2. The Pre-amp gain will need to be changed to 3MΩ if the signal is still off scale.

1.3 Cross-section Experiments

1.3.1 Absorption of Rb resonance radiation by atomic Rb

In this first experiment you will make an approximate measurement of the cross-section for the absorption of rubidium resonance radiation by atomic rubidium. The measured value will then be compared with the geometric cross-section and the value calculated from theory.

The apparatus should be arranged as shown in Figure 1.3.1. The linear polarizer and the quarter wave plate should be removed since they will not be needed for this experiment. The cell heater should be off, and the apparatus allowed to come to equilibrium. It may be necessary to insert a neutral density filter before the absorption cell to prevent saturation of the detector amplifier.

Set the cell heater to 300 K, and allow thermal equilibrium to be established. It will take about 30 minutes for the temperature to become stable. Measure the intensity of the optical signal taking care to record all amplifier gain settings. Repeat the measurement in

Table 1.2: Density of rubidium atoms over solid or liquid rubidium as a function of temperature

Temperature, K	Density, atoms/cubic meter
290	3.3×10^{15}
300	1.1×10^{16}
310	2.9×10^{16}
320	7.5×10^{16}
330	1.8×10^{17}
340	4.3×10^{17}
350	8.3×10^{17}
360	1.5×10^{18}
370	3.7×10^{18}
380	6.3×10^{18}
390	1.2×10^{19}
400	2.4×10^{19}

temperature increments of 10 K, taking care that thermal equilibrium is reached between readings. Repeat the series of measurements a few times, increasing and decreasing the temperature

Determine the density of atomic rubidium in the cell as a function of temperature from Table 1.2 and fit the data to an equation of the form

$$I = ae^{-b\rho} \quad (1.1)$$

where ρ is the density of atomic rubidium in the cell. From the value of b determine the cross-section for the absorption of rubidium resonance radiation by atomic rubidium.

Compare your result with the calculated value of the cross-section and with the geometrical cross-section.

It can be seen from the plot that above a density of about 200×10^{16} there is no further decrease in the intensity of the transmitted light. Ideally the cell should be optically thick, and no light should be transmitted. The light that is transmitted does not fall within the absorption profile of the rubidium in the cell, and hence gets through the cell and causes this background.

This radiation comes from the wings of the emission line and from the buffer gas in the discharge lamp. In order to correct for this a constant detector output voltage must be subtracted from all readings, and the plot and fit will be limited to the first seven points. The result is shown in Figure 1.5.

$$I = 1.36e^{-0.040\rho} \quad (1.2)$$

The length of the absorption path was about 2.5 cm giving a result

Table 1.3: Sample Data. Output voltage versus temperature.

Temperature, K	Detector Output, Volts
300	1.57
310	1.31
320	1.06
330	0.72
340	0.52
350	0.24
360	0.17
370	0.14
380	0.13
390	0.12
400	0.12

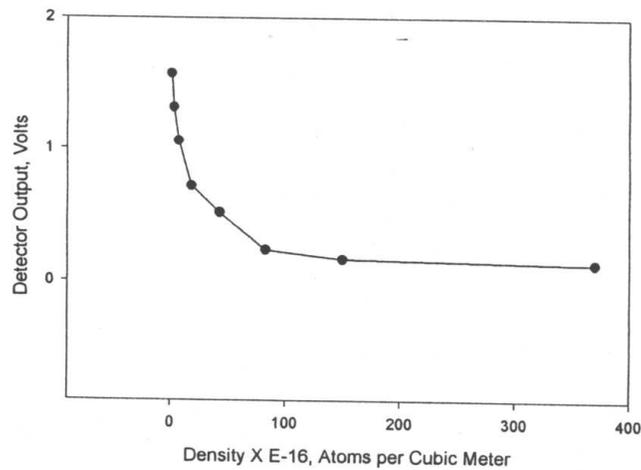


Figure 1.4: Plot of Sample Data

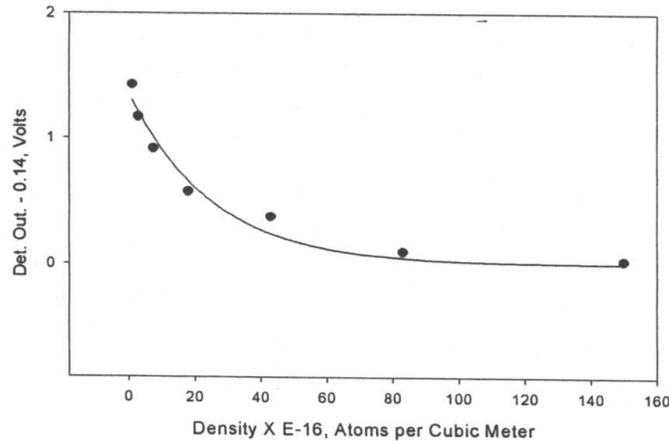


Figure 1.5: Plot of Sample Data with background correction. You may want to use a semi-logarithmic display instead

$$0.025\sigma \times 10^{16} = 0.040 \quad (1.3)$$

and

$$\sigma = 1.6 \times 10^{-16} m^2 \quad (1.4)$$

This can be compared with the result calculated from the equations in section 2C of the TeachSpin Optical Pumping Manual, using a Doppler width at 350 K of about 550 MHz, and a center frequency of about 3.77×10^{14} Hz. This corresponds to a center wavelength of 795×10^{-9} m. The resulting maximum cross-section is $\sigma_0 = 15 \times 10^{-16} m^2$. A more detailed calculation of the cross-section is in the literature [?], and a value of about $10 \times 10^{-16} m^2$ is given there. The geometrical cross-section is about $(10^{-10})^2 = 10^{-20} m^2$. Notice that the resonant cross-section is much larger than that normally associated with atomic scattering processes. As a point of interest the value of the absorption cross-section for sodium resonance radiation in atomic sodium is $12 \times 10^{-16} m^2$ [?].

Care needs to be taken in the interpretation of these results, since the cross-sections involved are somewhat ambiguous. The cross-section is a function of the frequency distribution in the absorption profile of the rubidium atom, and the intensity of the absorbed light will depend on the relationship of the intensity profile of the incident light to the absorption profile.

Therefore the measured result should be considered to be only approximate. These considerations are discussed in detail in the literature [?]. The main point here is to realize

that the cross-section for absorption of resonance radiation by an atom is much larger than what is usually taken as a measure of the geometrical cross-section.

The measured cross-section is about 10 times smaller than that calculated from theory. However this is not unreasonable considering the sources of error in the experiment. One of the largest of these is the rapid variation of the density of rubidium atoms in the cell as a function of temperature. This dependence, as shown in the Table 1.2, was calculated from graphical data contained in the book by Margrave[?], and is subject to considerable systematic uncertainty.

1.4 Experiments on Low Field Resonances

In all of the following experiments of this lab it will be necessary to apply a weak magnetic field along the optical axis of the apparatus. In order to do this satisfactorily, the apparatus must be located where the local residual magnetic field is as uniform as possible. The proposed location should be surveyed with a compass to check for gross inhomogeneity in the local field, and the orientation of the horizontal component of the residual field should also be determined. All iron or steel objects should be removed from the vicinity of the apparatus. The instrument should be placed on a table made with no magnetic material, such as the one supplied for this experiment by TeachSpin.

The optical axis of the apparatus should be oriented such that the horizontal component of the residual field is along this axis. The apparatus should be set up as shown in Figure 1.1, and the interference filter reinstalled. Be sure that the linear polarizer is ahead of the quarter wave plate in order to obtain circularly polarized light, and that the two are oriented properly.

In order to observe the zero-field transition, no RF is applied, and the magnetic field is swept slowly around zero. This is accomplished by varying the current in the sweep windings. The current through the main horizontal field coils should be set to zero. Adjust the current in the vertical compensating coils to achieve *minimum width* of the zero field transition. Also check the orientation of the apparatus along the horizontal component of the residual field by rotating the apparatus about the vertical axis and setting for minimum line width.

Set the cell temperature to 320 K and allow thermal equilibrium to be established. It is most convenient if the output of the optical detector is observed on the vertical axis of a storage oscilloscope, and a signal proportional to the current in the horizontal axis sweep coils is displayed on the horizontal axis. As will be shown later, optical pumping is a slow process, and during these experiments it will be necessary to use a very slow sweep rate for the magnetic field current.

Figure 1.6 shows the zero field resonance and the Zeeman resonances at a frequency of 0.0134 MHz.

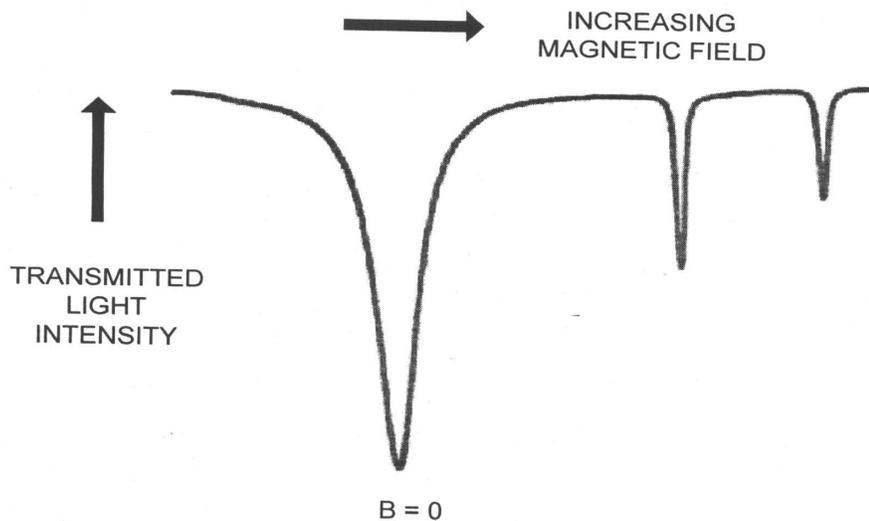


Figure 1.6: Zeeman resonances and zero field resonance at very low magnetic fields.

1.4.1 Measurement of the Nuclear Spins

There are two isotopes of rubidium, and they have different nuclear spins. We are going to pretend that we don't know their values, so we can measure them. In order to do this we must measure the g_F values from which the spins can be calculated. This can be done by measuring a single resonant frequency of each isotope at a known value of the magnetic field. The magnetic field will be determined approximately from the geometry of the field coils. Since nuclear spins are either integral or half-integral we need only an approximate value of the field.

We will use only the sweep field coils for this purpose, and their parameters are in Table 1.4:

Table 1.4: Field from the Coils

Mean radius	=	0.1639 m
B(gauss)	=	$8.991 \times 10^{-3} IN / \bar{R}$
		11 turns on each side

where I is the current in amps, N is the number of turns on each side, and \bar{R} is the mean radius of the coils. The coils satisfy the Helmholtz condition. At the sweep monitor terminals on the front panel, a voltage is presented that is numerically equal to the current in amps (the current passes through a one ohm resistor). Use this voltage as a measure of the sweep coil current.

First the residual magnetic field at the location of the absorption cell must be determined. Disconnect the main field coils so that there can be no current through them. Adjust the current in the sweep coils to center on the zero field resonance, and measure the current. From this and formulas of Table 1.4 calculate the value of the residual magnetic field. Be sure that there is no RF being applied.

An RF signal can now be applied to the RF coils, and its amplitude set to an arbitrary value. Later this amplitude will be adjusted for optimum transition probability. The frequency of the RF should be set to about 150 KHz. Sweep the horizontal magnetic field slowly increasing from zero, and search for the Zeeman resonances. Measure the current at which each resonance occurs.

An oscilloscope should be used to measure a signal proportional to the RF current at the connector on the cell holder. This signal is developed across a 50 ohm resistor that is in series with the RF coils, and therefore it is proportional to the amplitude of the RF magnetic field.

Measure the characteristics of the RF transitions as a function of the amplitude of the RF magnetic field, and determine the value that provides optimum transition probability[?].

The remaining data in this section should be taken using that value of RF magnetic field.

1.4.2 Low Field Zeeman Effect

With the main coils still disconnected, measure the transition frequencies of each isotope as a function of sweep coil current, and plot the results to determine that the resonances are indeed linear in the magnetic field. From the slope of the plots determine the ratio of the g_F -factors, and compare the measured ratio with that predicted by theory.

1.4.3 Sweep Field Calibration

For the remainder of the experiment it will be necessary to have a more precise value of the magnetic field than can be obtained from the geometry of the coils. In this section we will calibrate the sweep coils using the known gyromagnetic ratio values, $g_F = \mu/I\mu_0$, where μ_0 is the Bohr magneton, and the previous measurements.

From the previous measurements calculate the value of the magnetic field for each isotope from the resonance equation, and plot the magnetic field vs the current in the sweep coils. Fit the data to a straight line using a linear regression to obtain an equation for the magnetic field vs current.

It will now be necessary to make a calibration of the main field coils.

1.4.4 Main Field Calibration

Connect up the main coils so that their field is in the same direction as that of the sweep coils. The current control for the main coils is too coarse to allow the resonances to be

centered well using it alone. It will be necessary to use both the main coils and the sweep coils for this calibration. The voltage presented by the main coil monitor on the front panel (which is developed across a 0.5 ohm resistor) is one half of the main coil current in amps. Use this voltage as a measure of the main coil current.

Use both sets of coils to make measurements at resonance frequencies up to about 1 MHz, and use the sweep coil calibration to correct the measured fields for the residual field. Plot the data on a linear plot, and use a linear regression to obtain the best fit.

1.4.5 Sample Data

Residual magnetic field

The zero field resonance was determined to be at a sweep field current of 0.323 amp. From this and the above coil parameters the residual field is 0.188 Gauss. Since the rest of the experiment will be done with the magnetic field oriented opposite to the residual field, the above number must be subtracted from the values calculated from Equation 4B-1.

Nuclear spins

At an RF frequency of 150 KHz the measured currents for the two isotopes were 0.836 and 0.662 amp corresponding to magnetic field values of 0.504 and 0.400 Gauss. From each of these values a residual field of 0.188 Gauss must be subtracted yielding 0.316 and 0.212 Gauss.

The resonant frequencies are determined from

$$\nu = g_F \mu_o B / h \quad (1.5)$$

resulting in g_F values of 0.34 and 0.51. From Equation 2B-4 the corresponding nuclear spins are $I = 5/2$ and $I = 3/2$ with theoretical g_F values of $1/3$ and $1/2$ respectively.

1.4.6 Low field Zeeman effect:

The slopes of the two plots are in the ratio of 0.430/0.287 which gives a value of 1.498. The theoretical ratio is 1.5.

1.5 Higher Field Experiments

1.5.1 Quadratic Zeeman effect

The RF resonances of both isotopes will now be studied as the applied magnetic field is increased into a region where the energy level splitting is no longer linear in \mathbf{B} . Each of the zero field energy levels splits into $2F + 1$ sublevels, whose spacing is no longer equal. In this region there are $2F$ resonances whose splittings can be resolved. Thus for $I = 3/2$

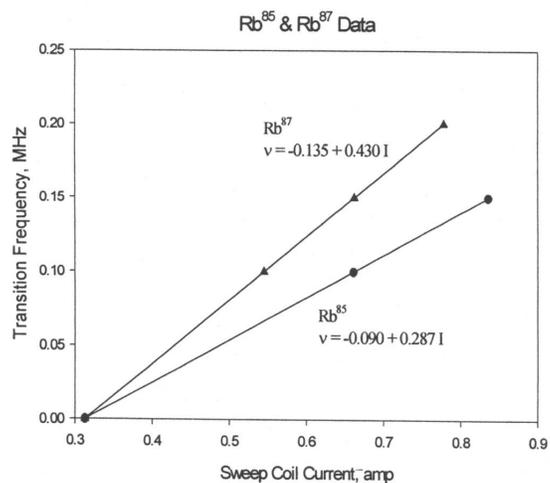


Figure 1.7: Low field Zeeman Effect.

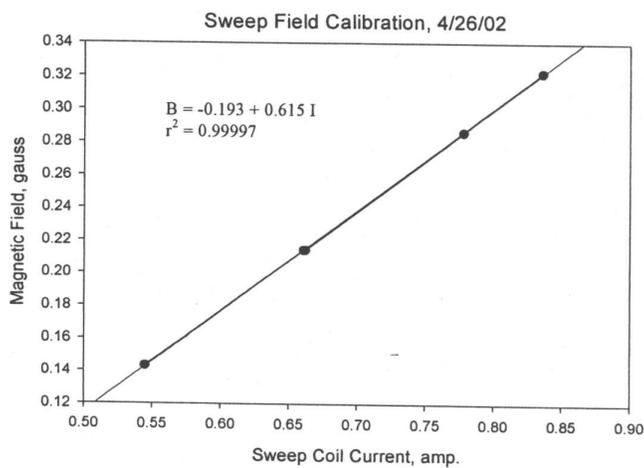


Figure 1.8: Sweep field calibration.

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Freq. MHz	Total field, Gauss	Sweep current, amp	Main current, amp	B from sweep coils, Gauss	B from main coils, Gauss	Isotope
0.2000	0.2858	0.321	0.0322	0.0047	0.2811	Rb ⁸⁷
0.2000	0.4287	0.316	0.0492	0.0017	0.4270	Rb ⁸⁵
0.3003	0.4291	0.306	0.0500	-0.0045	0.4336	Rb ⁸⁷
0.3003	0.6437	0.313	0.0740	-0.0002	0.6439	Rb ⁸⁵
0.4002	0.5719	0.197	0.0740	-0.0716	0.6435	Rb ⁸⁷
0.4002	0.8578	0.662	0.0740	0.2148	0.6430	Rb ⁸⁵
0.5002	0.7148	0.205	0.0900	-0.0667	0.7815	Rb ⁸⁷
0.5002	1.0722	0.785	0.0900	0.2906	0.7816	Rb ⁸⁵
1.0001	1.4291	0.121	0.1786	-0.1185	1.6482	Rb ⁸⁷

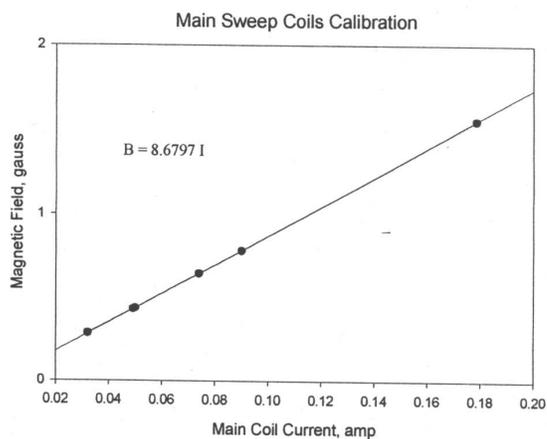


Figure 1.9: Sweep field calibration.

Table 1.5: Rb⁸⁷: Front Panel settings:

Output gain	=	20 X 10
ν	=	4.9874 MHz
RC	=	100 msec
RF amp gain	=	3 on dial
Sweep time	=	100 secs
Main field current	=	0.820 amp
Main field	=	7.117 Gauss

there are a total of six resonances with $\Delta F = 0$ and $\Delta M = \pm 1$, and for $I = 5/2$ a total of ten. These can all be observed. Their relative intensities depend on the pumping conditions.

The magnetic field at which these resonances can be observed can be approximately determined from the resonance equation,

$$\nu = g_F \mu_0 B / h, \quad (1.6)$$

and the current for the main field coils set from the previous calibration.

The energy levels and hence the more exact frequencies can be determined from the Breit-Rabi equation: Eq:1.7

$$W(F, M) = -\frac{\Delta W}{2(2I + 1)} - \frac{\mu_I}{I} BM \pm \frac{\Delta W}{2} \left[1 + \frac{4M}{2I + 1} x + x^2 \right]^{1/2} \quad (1.7)$$

where $x = (g_j - g_i) \mu_0 B / \Delta W$, and $g_i = -\frac{\mu_i}{I \mu_0}$. W is the interaction energy and ΔW is the hyperfine splitting[?].

Start with the main field current at zero, and set the sweep current to the center of the zero field transition. Then set the main field current to the desired value, and use the sweep field to observe the resonances. For a given frequency, measure the sweep field current corresponding to each resonance, and calculate the total magnetic field. If the first frequency that you try does not yield resolved resonances go to a higher frequency.

1.5.2 Sample Data

The observed spectrum is shown in Figure 1.10 and the calculated spectrum from the Breit-Rabi equation is shown in Figure 1.11 for Rb⁸⁷.

The absorption intensities in Figure 1.11 have been adjusted to match the observed spectrum. The Breit-Rabi equation can not be directly solved for x and hence B , but it can be easily solved by a computer program such as Maple or Mathematica. The results in Figure 1.11 were obtained using Maple 5.

The resonances occur at fields shown in the following table:

There is a systematic difference of 0.009 Gauss or about 0.14% between the calculated and measured total field values.

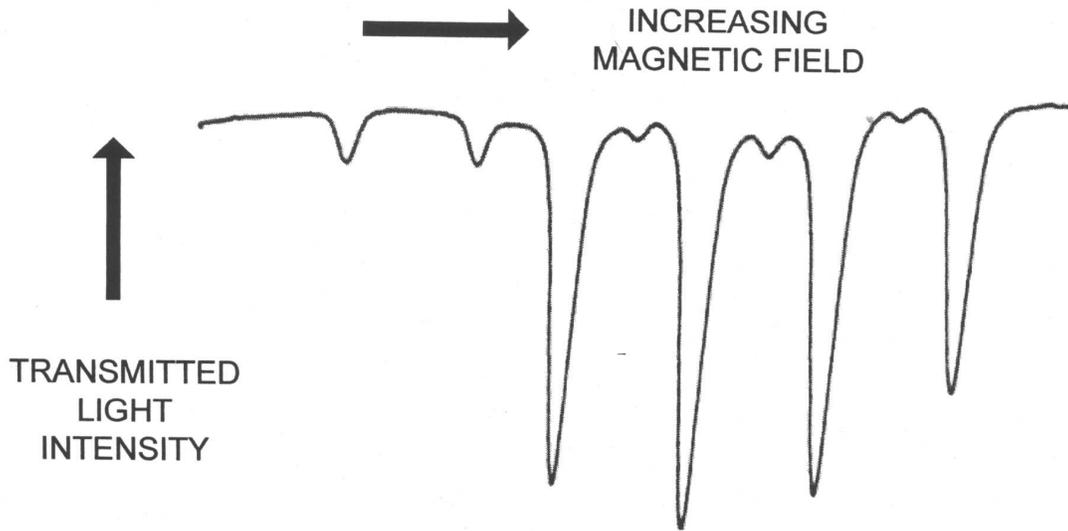


Figure 1.10: Observed spectrum of Rb^{87} at optimum RF power.

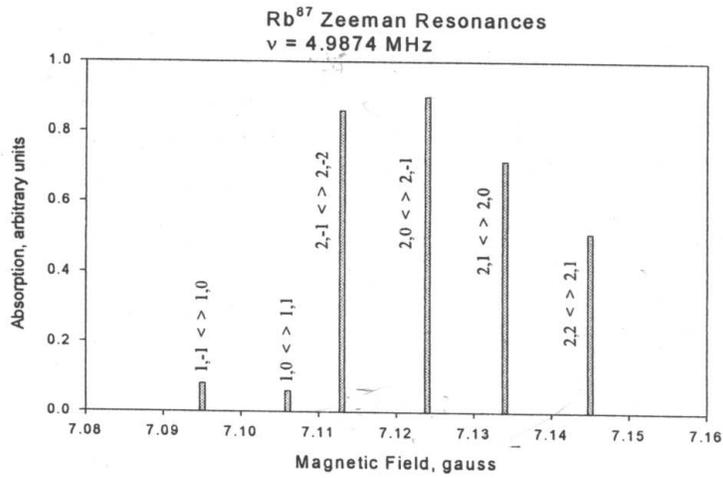


Figure 1.11: Calculated spectrum of Rb^{87} .

Table 1.6: Resonances

Sweep Field Current (amp)	Sweep Field (Gauss)	Total Field from calibration (Gauss)	Total Field from BR eqn. (Gauss)
0.292	-0.013	7.104	7.095
0.310	-0.002	7.115	7.106
0.321	0.004	7.121	7.113
0.339	0.016	7.133	7.124
0.355	0.025	7.142	7.134
0.373	0.036	7.153	7.145

Table 1.7: Rb⁸⁵: Front Panel settings:

gain	=	20 X 10
ν	=	3.3391 MHz
RC	=	100 msec
RF amp gain	=	3 on dial
Sweep time	=	100 secs
Main field current	=	0.820 amp
Main field	=	7.117 Gauss

The Rb⁸⁷ spectrum taken under the same conditions as above, except at higher RF power, is shown in Figure 1.12. The double quantum transitions, which occur midway between the single quantum transitions, are shown. Notice that the single quantum transitions have become broader because they are being over driven by the higher RF power.

The resonances occur at fields shown in the following table:

There is a systematic difference of 0,005 Gauss or about 0.07% between the calculated and measured total field values.

The Rb⁸⁵ spectrum taken under the same conditions as above except at higher RF power is shown in Figure 1.15. Here again, the double quantum transitions, which occur midway between the single quantum transitions, are shown. As with Ru⁸⁷, the single quantum transitions have become broader because they are being over driven by the higher RF power.

1.6 Experiments on Transient Effects

In order to observe transient effects it is necessary to either turn the pumping light off and on rapidly or turn the RF on and off while tuned to the center of a resonance. Here we will do the latter while tuned to the center of a low field resonance, and observe the

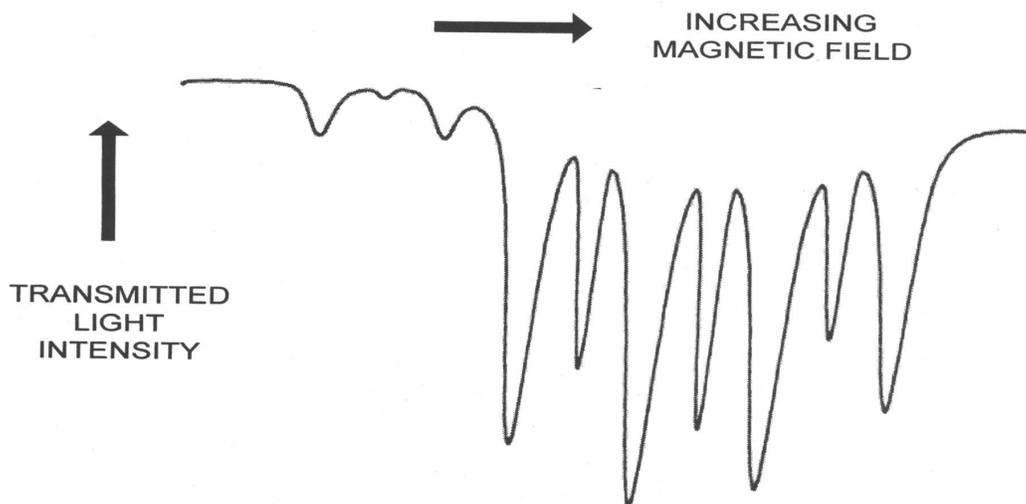


Figure 1.12: Observed spectrum of Rb^{87} at higher RF power showing double quantum transitions.

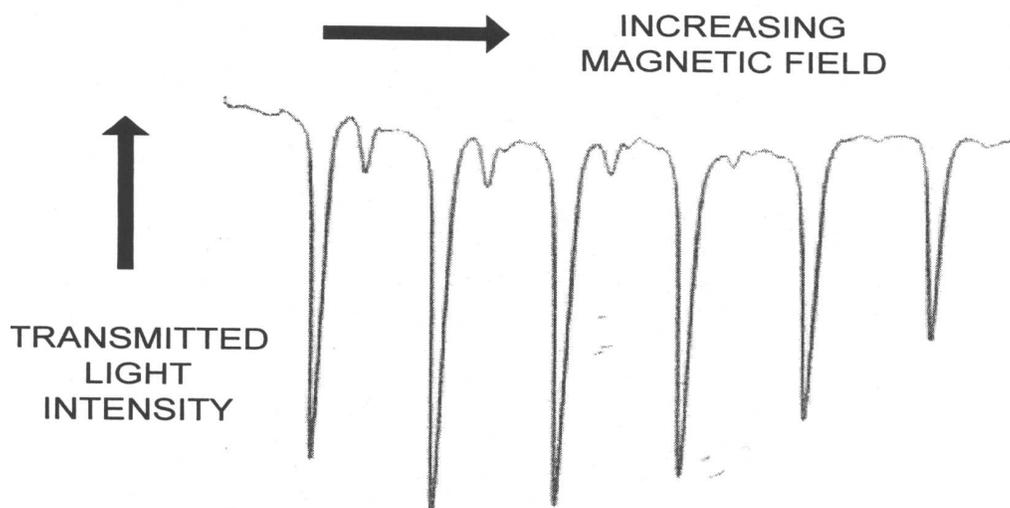


Figure 1.13: Observed spectrum of Rb^{85} at optimum RF power.

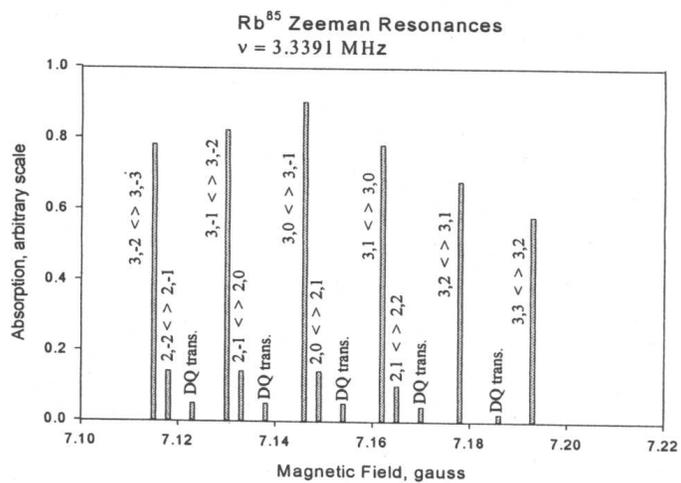


Figure 1.14: Calculated spectrum of Rb⁸⁵.

Table 1.8: Resonances

Sweep Field Current, amp	Sweep Field, Gauss	Total Field from calibration, Gauss	Total Field from BR eqn., Gauss
0.318 amp	0.003	7.120	7.115
0.344	0.019	7.136	7.130
0.369	0.034	7.151	7.146
0.395	0.050	7.167	7.162
0.421	0.066	7.183	7.178
0.446	0.081	7.198	7.193

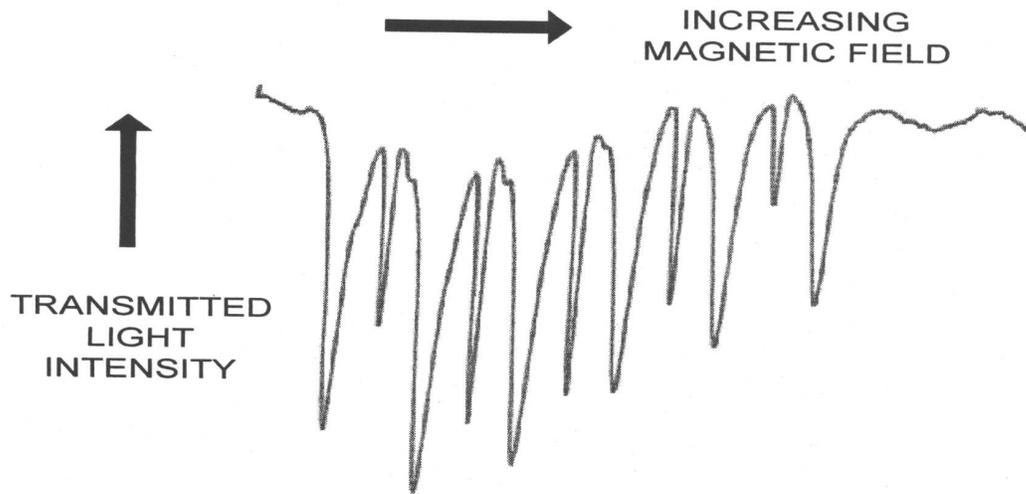


Figure 1.15: Observed spectrum of Rb^{87} at higher RF power showing double quantum transitions.

transmitted light intensity as a function of time.

1.6.1 Transient Phenomena

A square wave pulse of about 0 to +5 volts amplitude is connected to the RF modulation input on the front panel, and the frequency of the square wave set to about 5 Hz. The falling edge of the square wave should be used to trigger the sweep of a storage scope, and the output of the detector monitored. The following data was taken at a resonance frequency of 0.3 MHz.

The RF amplitude was taken as the voltage across the 50 ohm resistor in series with the RF coil. A typical result is shown in Figure 1.16. The upper trace shows the waveform that is gating the RF, and the lower shows the resulting optical signal.

When the RF is on all of the Zeeman levels are mixed, no optical pumping takes place, and the transmitted light intensity is a minimum. Turning off the RF allows pumping to begin, and the light intensity increases exponentially until a maximum value is reached. The time constant of this exponential is a measure of the optical pumping time. The characteristic value of the time will be found to be proportional to the intensity of the pumping light.

When the RF is turned on transitions will occur between the Zeeman sublevels and the population of the levels will be driven toward equilibrium. If the rise time of the RF envelope is short enough the populations will overshoot giving rise to the ringing shown

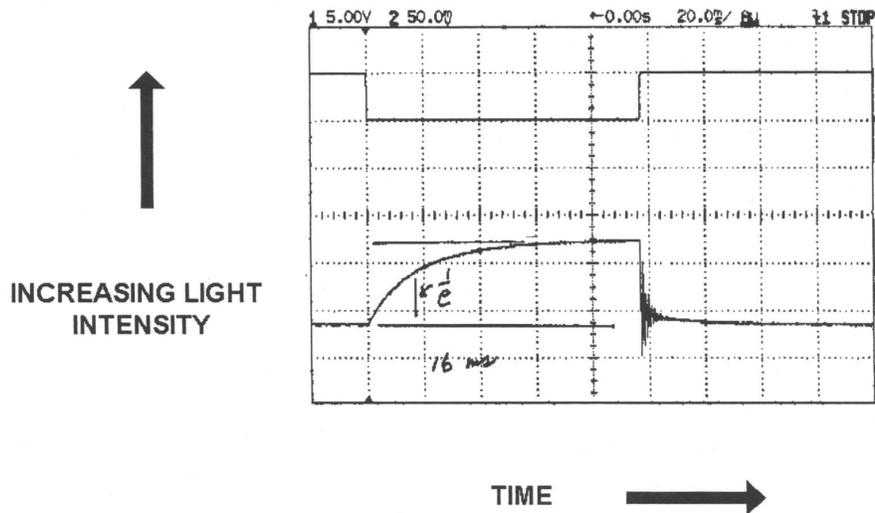


Figure 1.16: Time dependence of the transmitted light intensity vs. RF amplitude.

in Figure 1.16. The ringing damps out, and the light intensity approaches that for the un-pumped cell.

Figure 1.17 shows an expanded region of Figure 1.16 in the region of where the RF is turned on. It can be seen that the ringing is damped out followed by a longer damping time before the light returns to the un-pumped value.

Further expansion of the region around the RF turn on time yields a result shown in Figure 1.18. Here the ringing can clearly be seen, and its period measured. According to the earlier discussion this period should be linearly proportional to the reciprocal of the amplitude of the RF, since it corresponds to a precession of \mathbf{F} about the RF magnetic field. Figure 4D-4 shows this to be the case for both isotopes where the fit has been done by regression analysis in SigmaPlot.

At a given value of the RF magnetic field the ratio of the periods of the ringing goes inversely as the g_F factors, and the above data shows that this ratio is $989/641 = 1.54$ to be compared with a theoretical value of 1.50.

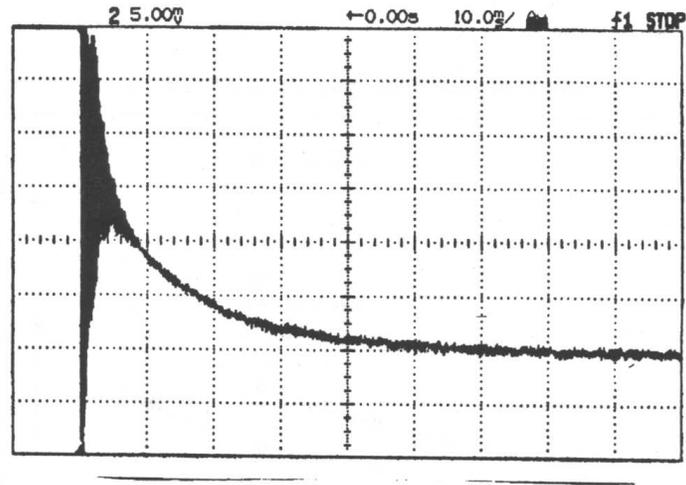


Figure 1.17: Expanded region where the RF is turned on.

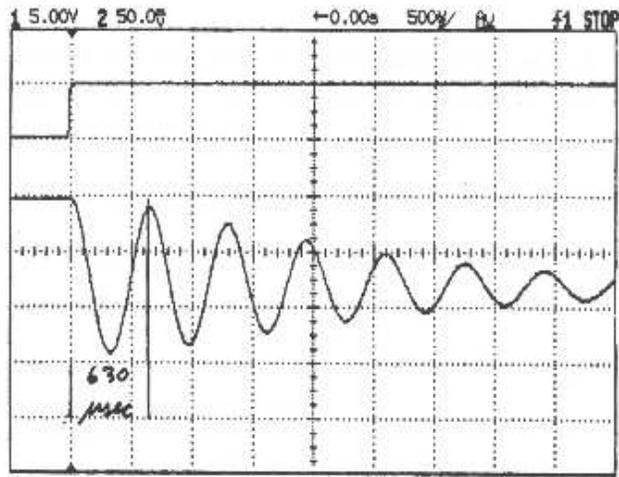


Figure 1.18: Expanded region where the RF is turned on.

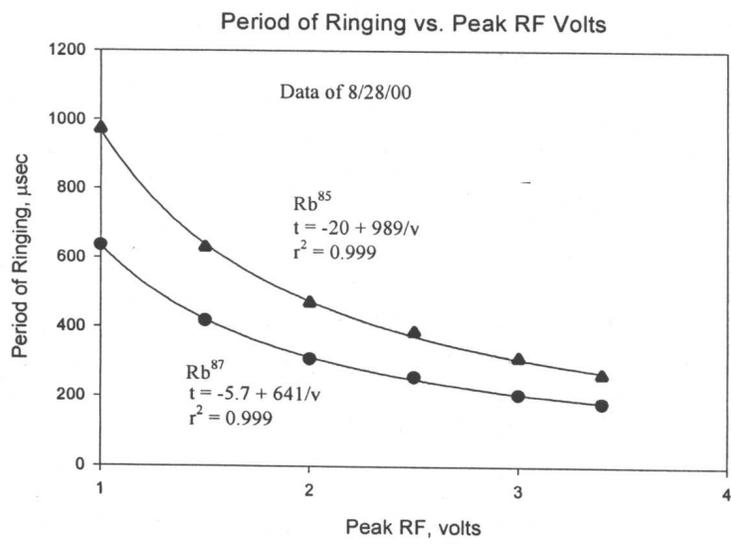


Figure 1.19: Period of ringing vs. peak RF volts.