Optical Pumping

PHYS352 Experimental Modern Physics
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1 Introduction

This optical pumping lab might be considered a mini-course in Atomic Physics, covering the following topics:

- Temperature Dependence of Atomic density via resonance absorption.

- Optical Pumping of Rubidium Atoms, ^{85}Rb and ^{87}Rb

- Magnetic Hyperfine Interactions in Rubidium

- Observation of transitions between different Zeeman states, driven by collisions or by an rf field

- Confirmation of Breit-Rabi Equation

- Observation of the Double Quantum Transitions

- Measurement of the Optical Pumping Times

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

In this lab you will be studying the ways to manipulate atomic spins. Typically, to magnetize some material one requires a strong magnetic field to align all the spins in the same direction. However, in this lab you will use light to achieve the same purpose, so strong magnet required. Historically, this was the first demonstration of all-optical preparation of a well-defined quantum state, and them1966 Nobel prize was awarded to Alfred Kastler for this discovery. Nowadays this techniques is applied in wide variety of fields, from initializing quantum registers for quantum computers to polarizing (through collisions) nuclear spins in a process called spin-exchange optical pumping and then using them for nuclear physics experiments (ask Prof. Todd Averett about his optical pumping system!) to imaging human lungs or insides of Egyptian mummies.

In this lab you will be working with atom called Rb - this is one of the heavier alkali metals, that have one unpaired electron in s-orbital in addition to a closed electron shell. As such, the energy levels for this electron is similar to a more familiar Hydrogen atomic levels, so you should be able to directly use most of the intuition from your Quantum class discussions. The main practical advantage is that Rb optical transitions are in near-infrared (hence the name "Rubidium" - deep red in Latin). Since there are many lasers and optical devices available in this spectral range, this makes Rb one of the favourite atoms for quantum information applications. A trove of useful information about Rb (and other alkali metals) can be found in Ref. [1].

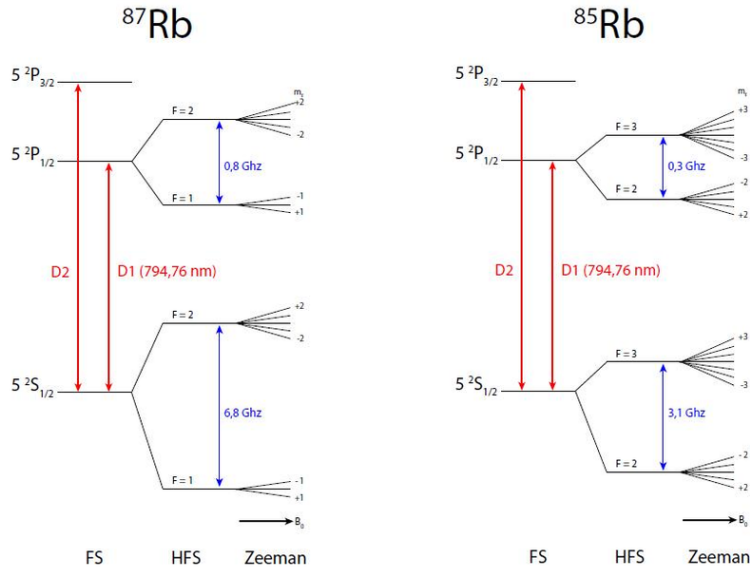## 1.1 Brief overview of Rb energy level structure

Figure 1: Energy levels of the ground and first excited electron states of ^{87}Rb and ^{85}Rb. The fine structure of the excited states gives rise to $5P_{1/2}$ and $5P_{3/2}$ states. However, in this lab we are mostly interested in the hyperfine structure, that manifests itself into splitting of the ground (and excited) states into different F states. Each of these hyperfine states can further split into different M sublevels in the presence of magnetic field.

As it was mentioned, Rubidium atom has just one valence electron, and the properties of this electron can be well approximated by those of an electron in a hydrogen atom. However, its nuclear properties are different, producing some notable variations. The interaction of electron spin S and the nuclear spin I give rise to a small difference in electron's energy depending on their mutual orientation, known as *hyperfine splitting*. Namely, it becomes more appropriate to use a total angular momentum $\vec{F} = \vec{S} + \vec{I}$ to characterize different atomic states. For $S = 1/2$ electron, there are two possible values of F for each I: $F = I \pm 1/2$, i.e., the originally degenerate S ground state becomes a doublet (in the absence of any external fields):

$$E(F = I \pm 1/2) = -\frac{\Delta W}{2(2I + 1)} \pm \frac{\Delta W}{2}, \tag{1}$$

where ΔW is the energy splitting between between the two $F = I \pm 1/2$ levels (third term). Note that the third term describes the common-mode shift of the two levels; this experiment is not sensitive to it.

Note on notation: Since this lab mostly focuses on the electron spin properties in the ground state with the electron angular momentum $L = 0$, we omit the discussion of the electron spin-orbit interaction that is responsible, for example, for the fine-structure of the electron exited states, as shown in Fig. 1. In general, rather than talking about electron spin S and electron orbital momentum L, one must use the total electron angular momentum $\vec{J} = \vec{S} + \vec{L}$. However, for the states with $L = 0$ total angular momentum is the same as electron spin. See the TeachSpin manual for a more detailed discussion. Note, however, that you may see the use of J in some of the equations, as we keep the standard notation.

in order to cause electron to "jump" from one energy level to another, it must receive or loose the exact amount of energy to compensate for the energy difference between the two levels. In many cases this extra energy is supplied or carried out in a form of electromagnetic field quanta. Since the energy of the photon

is determined by its frequency, we can always find the resonance frequency $f_{1,2}$ between the two energy levels E_1 and E_2 as:

$$2\pi f_{1,2} = |E_1 - E_2|/\hbar. \tag{2}$$

In this lab you will have to deal with two types of transitions. First one is an optical transition between the ground $5S_{1/2}$ and excited $5P_{1/2}$ electron states, and the second one is the transition between different magnetic sublevels of the ground state. Optical transitions will serve to prepare the atoms in the desired state, as well as to monitor the number of atoms in these states. The frequency measurements of the transitions between magnetic sublevels will allow you to characterize the their behavior in the magnetic field.

There are two stable Rb isotopes that have nuclear spin $I = 3/2$ for ^{87}Rb or or $I = 5/2$ for ^{85}Rb. The total angular momentum of the atom is therefore $F = I + S$ (for the electron ground state with $L = 0$). Because of the hyperfine interaction, each ground state splits into two energy levels, separating the states with F-values between —I-J— and I+J. In the isotope ^{85}Rb, the nuclear spin is $I = 5/2$, and the possible values of F are $F = 2$ (lower) and $F = 3$ (higher); in ^{87}Rb, $I = 3/2$ and therefore $F = 1$ or 2. This hyperfine splitting (HFS) is 10 time smaller than the fine structure splitting (hence the name). In the presence of an external field, the F-states split into as $2F+1$ sublevels as possible orientations of the vector $\vec{F}$ with respect to the magnetic field vector $\vec{B}$, due to the Zeeman effect. These magnetic substates have projections of the F quantum number along the B-direction M, with $M = -F, -F + 1... - 1M + 1... + F - 1, +F$.

In a weak B-field and in good approximation, the splitting is even, (i.e. the same energy splitting for all sub-magnetic states of one multiplet) and proportional to B. The exact value of the splitting (often referred as Zeeman splitting) depends upon the . The energy of each substate M in magnetic field B is shifted by:

$$E_M = g_F 0 BM, \tag{3}$$

where μ_0 is Bohr magneton, and g_F is called Lande g-factor that depends on specific values of atomic and nuclear magnetic moments, and thus will be different for different Rb isotopes. For the ground state of Rb atoms :

$$g_F = g_J \frac{F(F + 1) + 3/4 - I(I + 1)}{F(F + 1)}, \tag{4}$$

where $g_J = 2.002$ is the electron orbital Lande g-factor for the states with $J = S = 1/2$.

It is easy to see that in this regime the energy difference between the each consecutive M level does not depend on M. That means that if transitions are induced between these levels using, for example, resonant rf field, all of them occur at exactly same frequency:

$$f_B = \frac{E_M - E_{M-1}}{\pi\hbar} = \frac{g_F 0 B}{\pi\hbar}. \tag{5}$$

At higher field the calculations for the different magnetic sublevels is more complex. However, for a specific case of an electron in s-orbital, the further zeeman splitting of the hyperfine states $F = I \pm 1/2$ (as shown in Fig. 1) obeys the Breit-Rabi equation:

$$E(F = I \pm 1/2, M) = -\frac{\Delta W}{2(2I + 1)} + \frac{\mu_n}{g_I}BM \pm \frac{\Delta W}{2}\sqrt{1 + \frac{4M}{2I + 1}x + x^2}. \tag{6}$$

In addition to the original hyperfine splitting in Eq.(1), this expression includes the energy shifts of different magnetic sublevels M in the magnetic field. Here $x = (g_J - g_I)\mu_0 B/\Delta W$, where $\mu_n = $ is the nuclar magneton, and $g_I = -\frac{\mu_n}{I\mu_0} = -\frac{0.006}{I} \ll g_J$ is the nuclear g-factor. It is possible to see that for small magnetic field ($x \ll 1$), Eq.(6) can be approximated by Eq.(3). However, as B-field increases, the energy difference between two near magnetic sublevels is not longer proportional to M, and thus the transition frequencies between them become non-degenerate, as you will see yourself.
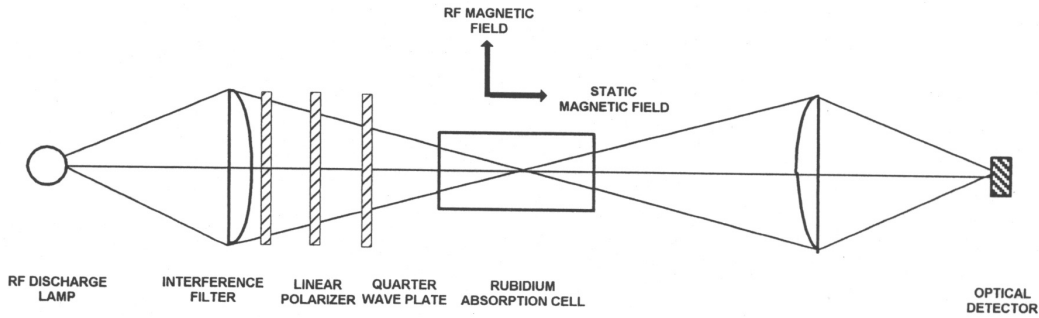
Figure 2: Apparatus arrangement for optical pumping.

1.2 Optical pumping arrangement

The experimental apparatus is shown in See Fig. 2. In this experiment you will use a Rb discharge lamp as a light source. Its output, after spectral filtering, collimating with a lens and circularly-polarizing the light (using a polarizer and a quaterwave plate), is directed into a heated Rb cell, in which all the measurements are done. This way, the frequency of light automatically matches the energy in Rb atoms contained in the experimental cell. Since we cannot access atomic states directly, all the information is extracted via observation of light transmission using a detector, placed after the cell. During the experiment the light will excite atoms into the excited state; after a very short time they will spontaneously decay back into the ground state, emitting spontaneous light (that we cannot detect). Since the original photons are absorbed in the process, we can roughly estimate the reduction in light power (i.e., in the number of photons) with the number of atoms absorbing this light. In the first activity – absorption cross-section measurements – you will change the number of absorbing atoms by changing the temperature of the Rb cell. However, we can also use the absorption of circularly polarized light to control (and also monitor) the preparation of atoms in a specific quantum state.

Right circular polarized photons carry one unit of angular momentum. Because of the momentum conservation that means that a photon with an angular momentum +1 must change the angular momentum of an atom by one when it is absorbed. That means that a circular polarized photons with positive angular momentum (σ_+ polarization) can only induce transitions with $\Delta M = +1$.

To understand the nature of optical pumping suppose the absorbing atoms can be represented by the simple spin system shown in Fig. 3, consisting of $F = 1$ ground state, and $F = 0$ excited state. In this case the ground state has three magnetic sublevels $M = 0, \pm 1$. Absorbed photons will take the electrons from the $M = -1$ ground state to the excited state, which then decays to equally to all three M states of the ground state. Since there is no path to take electrons from the $M = 0$ and $M = +1$ ground states back to the $M = -1$, the $M = -1$ becomes
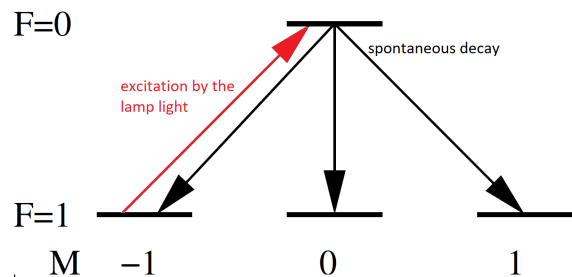

Figure 3: A simple spin system for which the ground state has total angular momentum 1, and the excited state has total spin 0. The excitation by right circular light is shown as are the three decay modes of the excited state.

depleted. Since absorption can only take place for the $M = -1$ state, the gas of absorbing atoms becomes more transparent and allows more light to reach the detector.

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	2

Table 1: Properties of the Rb isotopes.

The actual system that you will be studying is Rb. While this is clearly more complicated than the simple case of Fig. 3, the overall result will be quite similar, as most of the atoms will end up in the state with maximum $M = F$ state. You can intuitively understand that by assuming that atoms will be able to absorb photons, increasing their angular momentum by one, until they are in the state with maximum angular momentum, from which the absorption of a circularly polarized photon becomes impossible (see the discussion in the TeachSpin Manual. Some of the useful parameters of Rb atoms are shown in Table 1.

To determine that the system has been optically pumped one needs to find a means of de-pumping the maximum M state, and bring some of the atoms in the absorbing state. Upon being de-pumped the gas will absorb more readily and less light will be detected. In the experiment you will explore two depumping mechanisms.

Zero-field resonance One means of de-pumping is to remove any magnetic field. Then M is no longer a good quantum number, and collisions can easily change the orientation of the atom.

Rf transitions A second means to de-pump is to induce by an rf magnetic field transitions between neighbouring M states. That will redistribute the atomic population from the maximum M state. Note that this process requires that the frequency of the rf field matches the frequency difference between magnetic sublevels.

2 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 **??**. 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 temperature increments of 10 K taking care that thermal equilibrium is reached between readings. Repeat the series of measurements as many times as possible both increasing and decreasing the temperature

Determine the density of atomic rubidium in the cell as a function of temperature from Table 2 (or by using formulars from Eg.(1) in [1]).

Theoretically, we expect that the transmitted light will fall exponentially with the density of atomic Rb in the cell ρ:

$$I_{out} = I_{in}e^{-\sigma\rho\ell}, \tag{7}$$

where σ is the absorption cross-section, and $\ell \approx 2.5$ cm is the optical path inside the Rb cell.

Table 2: Density of rubidium atoms over solid or liquid rubidium as a function of temperature

Temperature, K	Density, atoms/cubic meter
290	4.0×10^{15}
300	1.2×10^{16}
310	3.14×10^{16}
320	8.0×10^{16}
330	1.9×10^{17}
340	4.4×10^{17}
350	9.5×10^{17}
360	1.2×10^{18}
370	3.9×10^{18}
380	7.5×10^{18}
390	1.4×10^{19}
400	2.5×10^{19}

Ideally, you expect the light intensity to fall exponentially to zero as the density of atoms increases. However, it is most likely that your result will look similar to the trace in Fig. 4, in which there is no further decrease in the intensity of the transmitted light above the certain density. Why this happens? The reason is that the discharge lamp emits light in a broad spectrum, and some portion of its light does not fall within the absorption profile of the rubidium in the cell, and hence gets through the cell and causes this background.
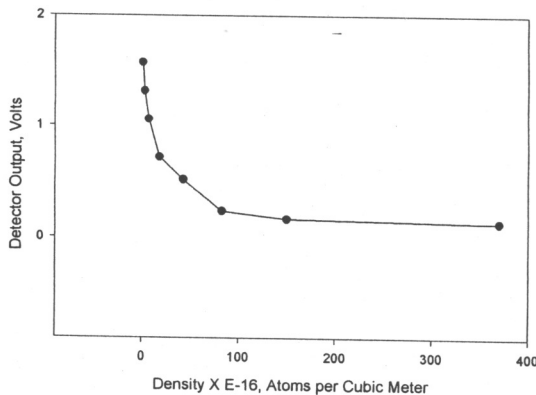

Figure 4: Plot of Sample Data

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 can be subtracted from all readings, or included as a part of the fitting function to extract the absorption cross-section value from your experimental data.

Your measured results 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 yeild the value of about 10×10^{-16} m^2. 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.

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 of the atoms. Therefore the measured result should be considered to be only approximate. 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.

It is likely that your measured value of the cross-section will be considerably 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.

3 Experiments with 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 2, 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.

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 5 shows the zero field resonance and the Zeeman resonances at a frequency of 0.0134 MHZ.

3.1 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. We can calculate the magnetic field B(in Gauss) they produce assuming they are in Helmholtz configuration:

$$B = 8.991 \times 10^{-3} IN/\overline{R}, \tag{8}$$

and their where $\overline{R} = 0.1639$ m is the mean radius of the coils, I is the current in amps, $N = 11$ is the number of turns on each side.
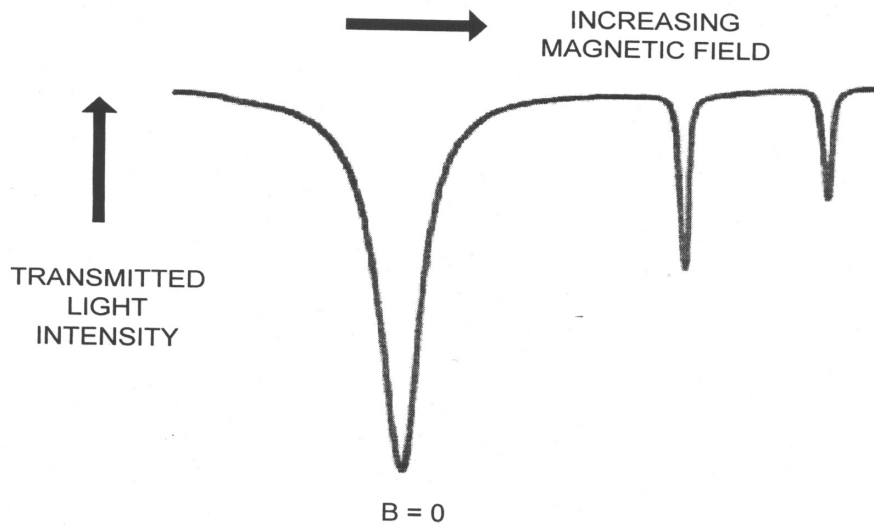
Figure 5: Zeeman resonances and zero field resonance at very low magnetic fields.

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 Eq.(8) 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 strong resonance without significant broadening. The remaining data in this section should be taken using that value of RF magnetic field.

With the main coils still disconnected measure the transistion frequencies of each isotope as 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.

3.2   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 g_F values 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.

3.3   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.

3.4   Sample Data

3.4.1   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.

3.4.2   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

$$\nu = g_F \mu_o B / h \tag{9}$$

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.

3.5   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.
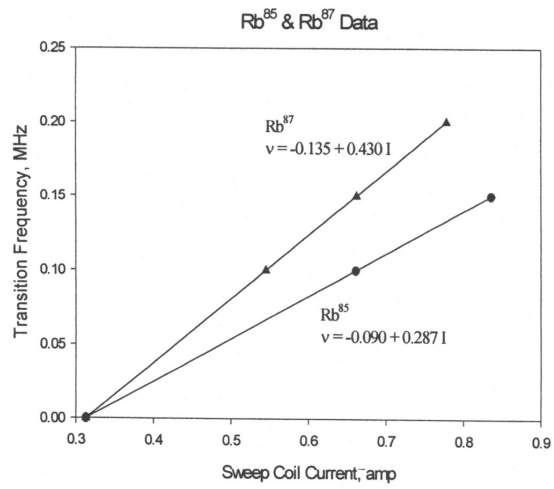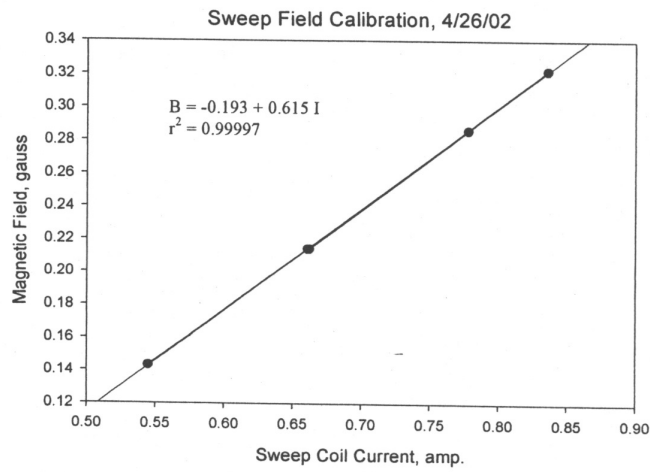
Figure 6: Low field Zeeman Effect.

Figure 7: 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}
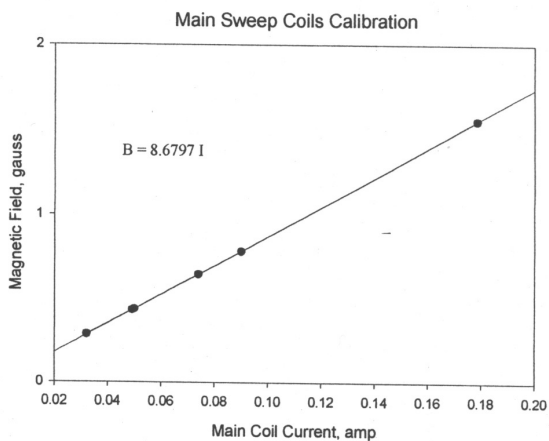
Figure 8: Sweep field calibration.

Table 3: Rb^{87}: Front Panel settings:

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

4   Higher Field Experiments

4.1   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 **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 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:

$$\nu = g_F \mu_0 B / h \tag{10}$$

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:6.

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.

4.2   Sample Data

The observed spectrum is shown in Figure 9 and the calculated spectrum from the Breit-Rabi equation is shown in Figure 10.

The absorption intensities in Figure 10 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 Mathmatica. The results in Figure 10 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.

The Rb^{87} spectrum taken under the same conditions as above except at higher RF power is shown in Figure 11. Here 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 overdriven by the higher RF power.
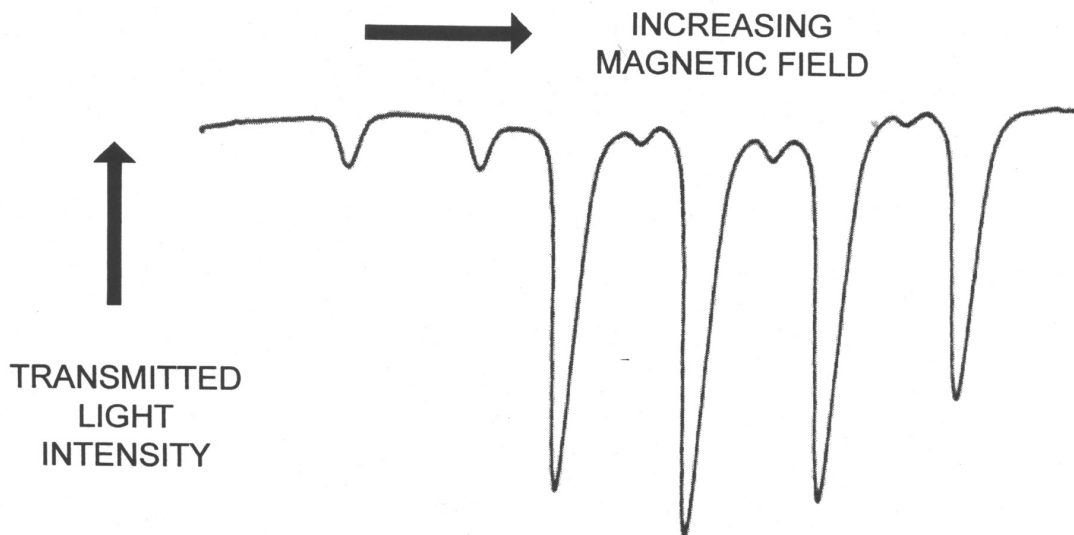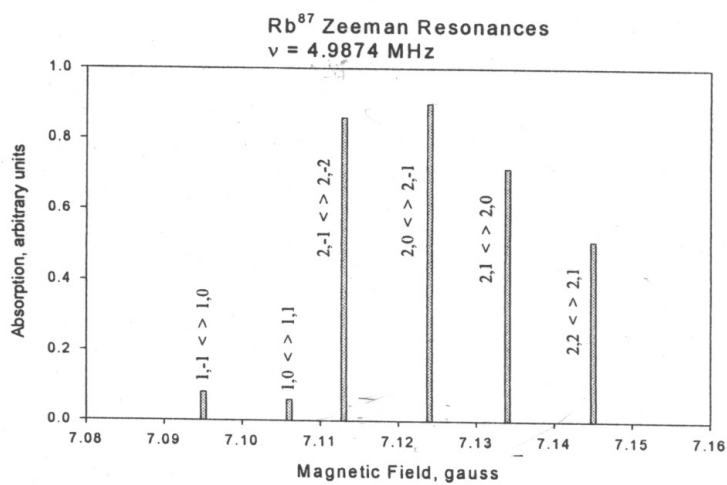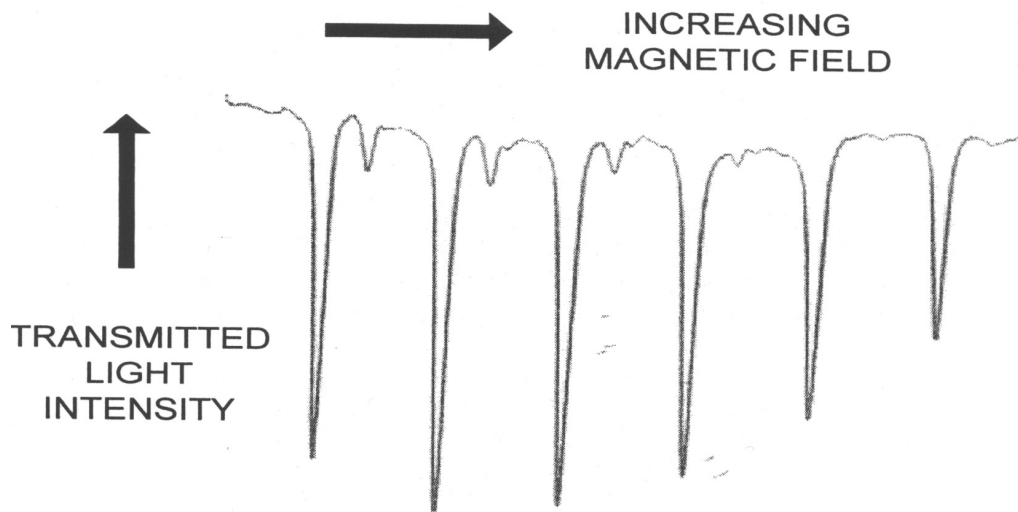
Figure 9: Observed spectrum of Rb[87] at optimum RF power.

Figure 10: Calculated spectrum of Rb[87].

Table 4: 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 5: Rb^{85}: 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
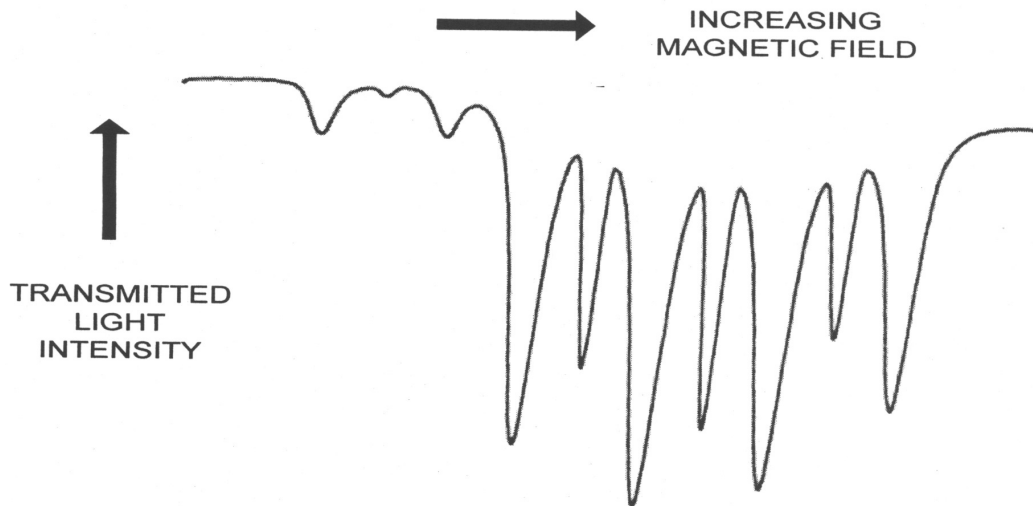
Figure 11: Observed spectrum of Rb^{87} at higher RF power showing double quantum transitions.

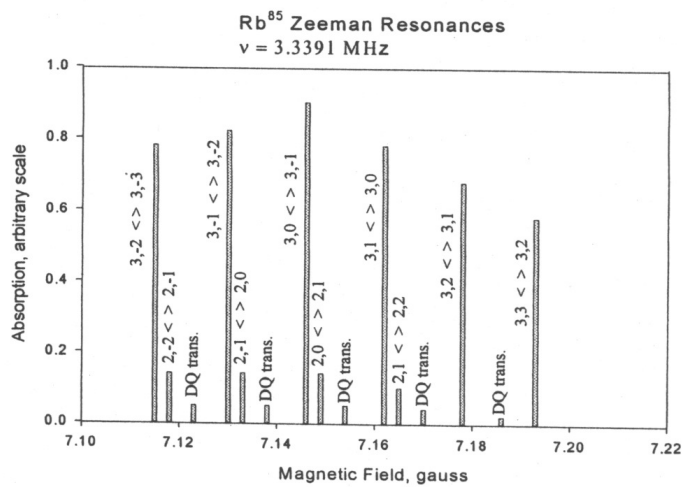Figure 12: Observed spectrum of Rb^{85} at optimum RF power.

Figure 13: Calculated spectrum of Rb^{85}.

Table 6: 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
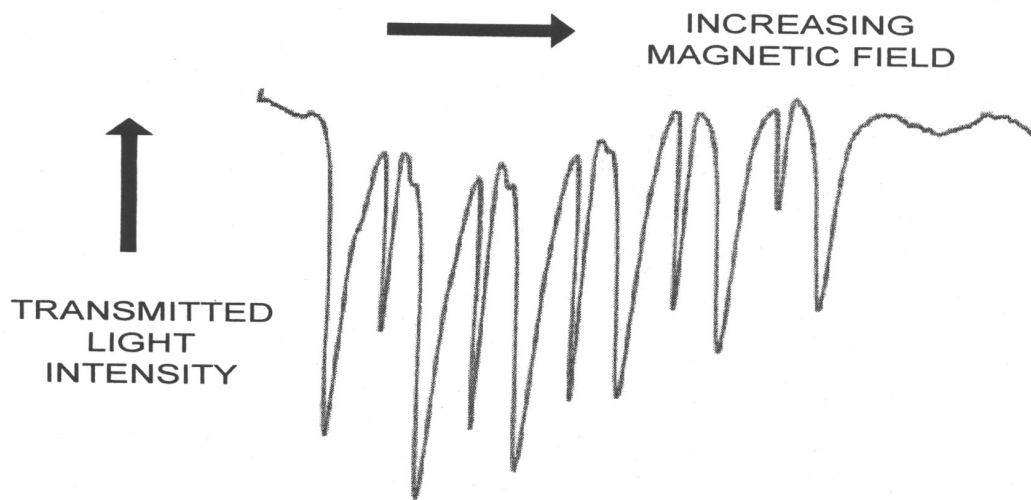
Figure 14: Observed spectrum of Rb[87] at higher RF power showing double quantum transitions.

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 Rb[85] spectrum taken under the same conditions as above except at higher RF power is shown in Figure 14. Here 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 overdriven by the higher RF power.

5   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 transmitted light intensity as a function of time.
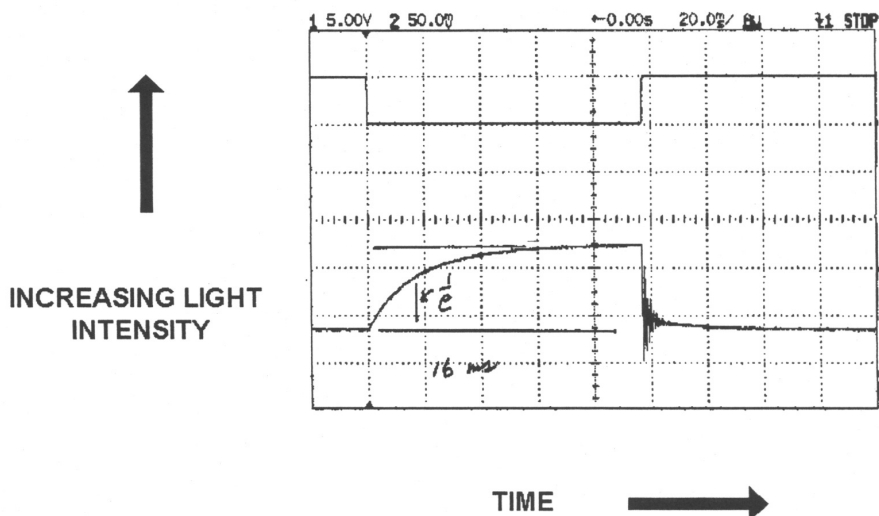
Figure 15: Time dependence of the transmitted light intensity vs. RF amplitude.

5.1 Sample Data

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 15. 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 in Figure 15. The ringing damps out, and the light intensity approaches that for the unpumped cell.

Figure 16 shows an expanded region of Figure 15 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 unpumped value.

Further expansion of the region around the RF turn on time yields a result shown in Figure 17. Here the ringing can be 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
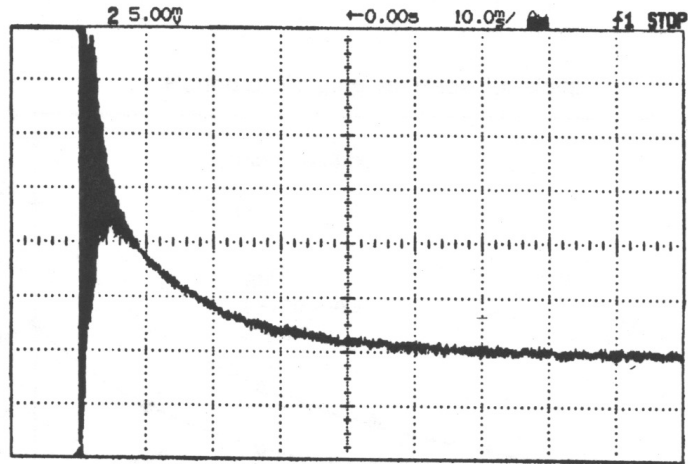
17

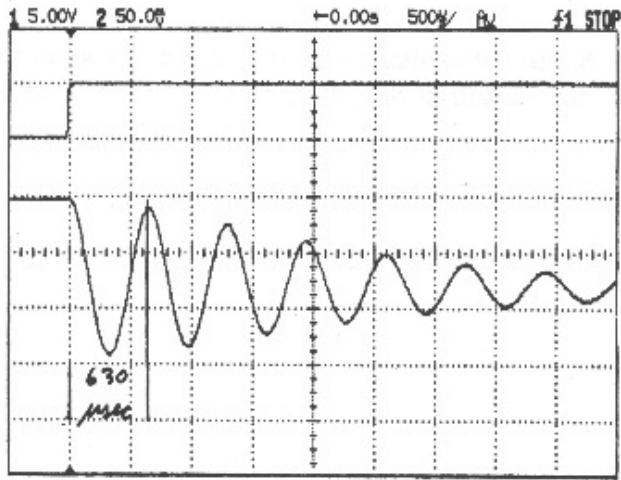Figure 16: Expanded region where the RF is turned on.
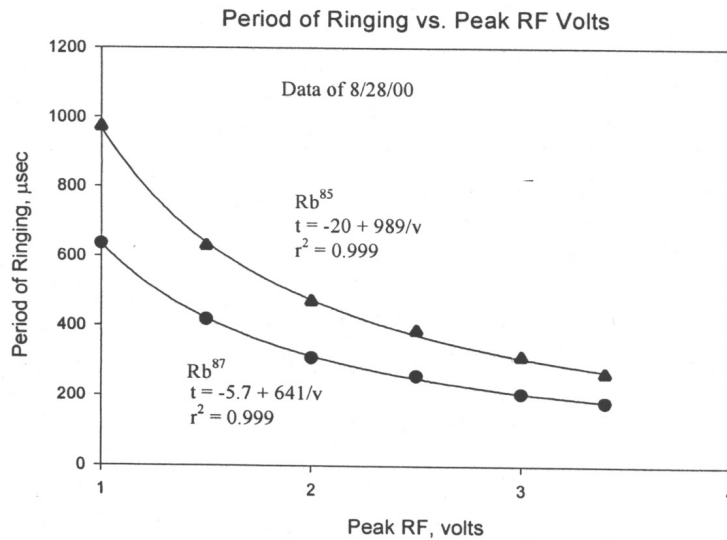

Figure 17: Expanded region where the RF is turned on.

Figure 18: Period of ringing vs. peak RF volts.

value of 1.50.

References

[1] "Alkali D Line Data" https://steck.us/alkalidata/ (accessed April 2, 2022).

6 Appendix: Setting up the Optical Pumping Apparatus

There is a good chance that all the connections are made already in the beginning of the experiment (check with your instructor when it doubt). If for some reason the wires are disconnected, 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 then 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.