

DIODE LASER SPECTROSCOPY

1. Introduction

1.1 Atomic Physics Primer

Diode lasers are used extensively in research and technology today. It is therefore important for physicists to know how to use them and be familiar with some of their applications. Even though you'll have a brief introduction to diode laser technology, the focus of this exercise will not be on learning how the laser works. Instead, it will be on how to use the laser in spectroscopic applications. You will begin with some exercises that teach laser fundamentals, laser control and some basic spectroscopic measurements. Once familiar with the operation of the laser and the optical system, you will perform a detailed investigation of the hyperfine structure of rubidium and the Zeeman Effect.

To perform this experiment, you need to know some atomic physics. Most of this information can be found in introductory textbook on quantum mechanics, such as those listed in the references. The Scientific American article in the references is also informative. The ground-state electronic configuration of Rb consists of closed shells plus a single 5s valence electron. This gives a spectrum that is similar to hydrogen. With just a Coulombic potential, the Schrödinger equation yields energy levels that depend only on the principle quantum numbers, n . However, the degeneracy of the principle quantum numbers is lifted when several corrective effects are included. The first involves a relativistic correction to the kinetic energy. The second two corrections affect only the s -orbital: The Darwin term, which is a smearing out of the electrostatic interaction between the electron and nucleus due to rapid quantum fluctuations, and the Lamb shift arises from a quantum electrodynamic interaction between the electron and the vacuum state. Finally, there is an interaction between the electron's spin and its orbital angular momentum, which is also relativistic in nature, known as spin-orbit coupling. Because of this coupling, the z -components of the orbital angular momentum L and spin angular momentum S are no longer represented by good quantum numbers (i.e., they no longer have definite values, and wavefunctions characterized by these quantum numbers are not eigenfunctions of the Hamiltonian.) However, these quantum numbers are replaced by two new quantum numbers, total angular momentum $J = L + S$ and its z -component J_z . The spin-orbit interaction splits the p -orbital into two levels, characterized by J . For $L = 1$ and $S = 1/2$, the level with $J = 3/2$ is higher in energy than the one with $J = 1/2$, and the 5s level in between them. The modifications to the non-relativistic energy-level from the Schrödinger equation, referred to as fine structure, are qualitatively displayed in Figure 1.

The different energy levels are labeled by "term states" with the notation $^{2S+1}L_J$ where L is the spectroscopic notation for the angular momentum quantum number (i.e., S, P, D, \dots , for orbital angular momentum quantum number $L = 0, 1, 2, \dots$). With this

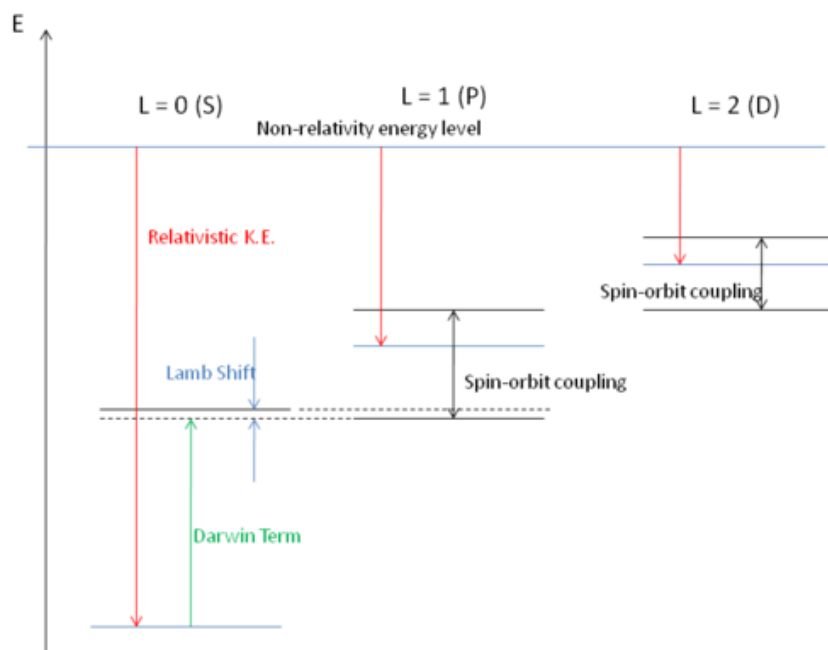


Figure 1. Generic energy-level diagram showing the corrections to the non-relativistic orbitals.

notation, the ground state of the 5s electron is $^2S_{1/2}$, and the first excited state is $^2P_{3/2}$. The $^2P_{1/2}$ level lies below the $^2S_{1/2}$ level because of the Lamb shift.

There is one more interaction that must be included, and this leads to what is referred to as hyperfine structure because the energy shifts are much smaller than those associated with the fine structure. The Darwin term discussed above is a modification of the electrostatic from the nucleus seen by the electron due to quantum fluctuations. If the nucleus has a magnetic moment, it produces a magnetic field at the site of the electron, and the electron's energy also depends on the orientation of its spin with respect to this field in addition to the Darwin term. If the hyperfine structure is small compared to the fine structure (i.e., IJ coupling), I and J , where I is the nuclear spin and J is the same as above, are good quantum numbers, and the dominant term in the interaction between the nuclear spin and the electron is expressed by a term in the atomic Hamiltonian of the form $\mathcal{H}_{hyp} \propto \mathbf{I} \cdot \mathbf{J}$. Similar to the case with spin-orbit coupling, the degeneracy of the fine structure is further split into a series of levels characterized by the total angular momentum $F = I + J$. The energy levels are shifted with respect to the fine structure by an amount given by

$$E = \frac{C}{2} [F(F+1) - I(I+1) - J(J+1)]$$

where C is the hyperfine structure constant and F has the values $|I - J|, |I - J + 1|, \dots, |I + J|$. Notice the separation between adjacent levels is $E(F) - E(F-1) = CF$.

Rubidium has two naturally occurring isotopes: ^{85}Rb (72 percent abundance) with nuclear spin quantum number $I = 5/2$, and ^{87}Rb (28 percent abundance) with $I = 3/2$. Since the nuclear spin is different, each isotope will have a unique hyperfine structure, and spectroscopy on a gas of Rb atoms with the naturally occurring composition will show both spectra superimposed on each other. For ^{85}Rb , the $^2P_{3/2}$ level is split into the series of levels identified with $F = 4, 3, 2, 1$. Qualitative energy diagrams for both isotopes of Rb are shown in Figure 2. Transitions, which are subject to the selection rules $\Delta F = \pm 1, 0$ with no $F_i = 0 \leftrightarrow F_f = 0$, show up as absorption features in the spectra. An example is such a spectra is shown in Figure 3 with the features identified by the transition and isotope. Notice that each isotope has two transitions, and we expect transitions between same levels in the two isotopes to have similar energies. Because these features are Doppler broadened, the hyperfine structure of the $^2P_{3/2}$ level is unresolvable. Later, you will learn a technique for removing the Doppler broadening from the spectra to observe the hyperfine structure in the $^2P_{3/2}$ level.

1.2 Important Operational Considerations

Before using with the laser, you should be familiar with the physics associated with the diode lasers. The laser controls are complicated, and this is important for understanding how these controls work. Appendix 1 in the DSL Supplement document presents a brief

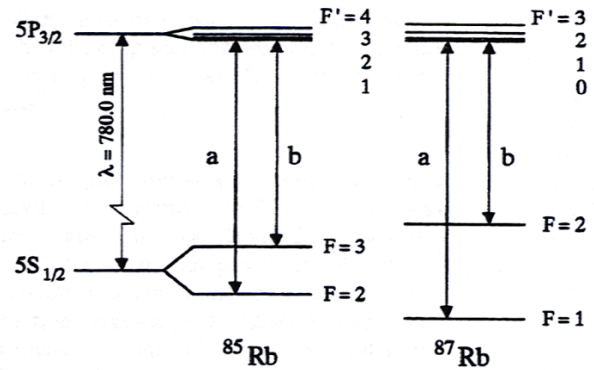


Figure 2. Qualitative energy diagram for the D_2 transitions of the two stable isotopes of rubidium.

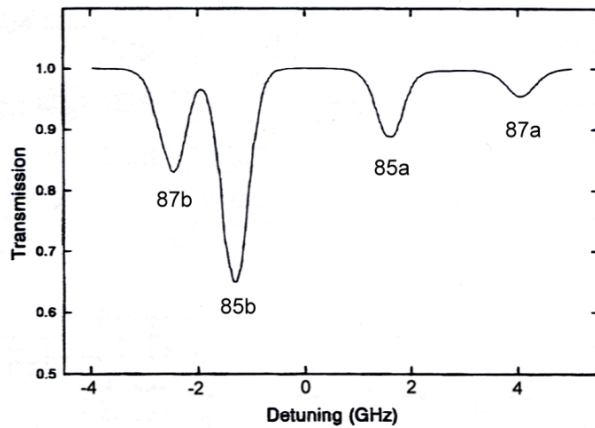


Figure 3. Absorption spectrum for a Rb vapor cell with the transitions in figure 2 identified.

introduction to those fundamental concepts.

Throughout this lab you must follow all safety procedures regarding usage of lasers. Failure to do so could result in serious injury to your or another person's eyes. Before working with the laser, you are required to go on-line and complete the Laser Safety training offered by EH&S. Certification that you have taken and passed this training course is required before you can begin working with the laser.

The following safety procedures must be followed whenever you are in the laser room.

1. As soon as you enter the laser room, always shut the door and put on your safety goggles before working with any of the equipment. The goggles are highly translucent to visible light, allowing you to easily see the equipment. This helps insure that the goggles are being worn when you turn the laser on later and forget about the goggles. The laser light has a wavelength close to 780 nm, which is nearly invisible. Everyone in the room must wear safety goggles.
2. At the same time you put on your goggles, remove any rings, watches, bracelets and any other objects that could reflect the laser light. This reduces the possibility of inadvertent reflections into someone's eye.
3. Finally, always remember to place the yellow laser warning sign on the side-room entry door from the 142 lab before tuning on the laser. The laser is operating and potentially dangerous whenever diode current is flowing. The doors to the laser room should remain closed at all times when the laser is running. If someone knocks on the door, turn off the laser current before opening the door. The door connecting to room 2029 should remain closed at all times. When leaving the laser room, make sure that all equipment is shut off, and do not leave the equipment running for extended periods of time (such as overnight).

Before working with the laser, Rb cell and optical system, it is important to become familiar with these instruments and their operation. Appendix 2 in the DSL Supplement provides an overview of the apparatus. Read this material carefully because the terminology will be used throughout the remainder of this manual.

The laser and the optical system (i.e. lenses/mirrors, Rb cell, photodiode detectors) are delicate instruments and have been carefully aligned. To prevent damage to the laser and/or misalignment, the following procedures must be followed. Failure to do so could lead to a significant loss of time and could impact your ability to complete this lab.

1. Never remove the plexiglass box, which protects the laser. The laser has been aligned by the lab staff, so there is no need to make any adjustment to the laser itself. If the laser appears to be malfunctioning in any way, contact the lab staff immediately. Do not attempt to make any adjustments to the laser.
2. Before turning on the main power switch to the laser controller, make sure the laser current power switch is in the off position (toggle switch should be down). **Never turn on the main power switch with the diode current toggle switch ON. This could damage the laser or controller electronics.**
3. Always raise and lower the diode current slowly, and monitor the current level with a digital multimeter (DMM). Do not toggle the current on or off, and do not allow the diode current to exceed 70 mA.
4. In section 2, do not touch or disturb any of the optical apparatus (i.e. lenses, mirrors, filters, beam splitters, Rb cell, or photodiodes) unless instructed to do so in this manual. Doing so may disturb the alignment, requiring realignment.

In the following sections, there will be some questions in *italics*. These questions are meant to guide your understanding of the material. Unless otherwise stated, they needn't be answered in your lab report. However, if you cannot answer a question, you should speak to the TA or one of the lab staff. The answers to these questions are fundamental to your understanding of the following material.

2. Basic Absorption Spectrum

2.1. Rb Absorption Spectrum with Mode Hopping

You will begin by discussing some basic spectroscopic measurements on Rb. Although important, this section is only a *discussion*. The actual lab exercise begins in Section 2.2. The optical system in Figure 4 shows a laser beam directed through a cell containing the Rb gas.

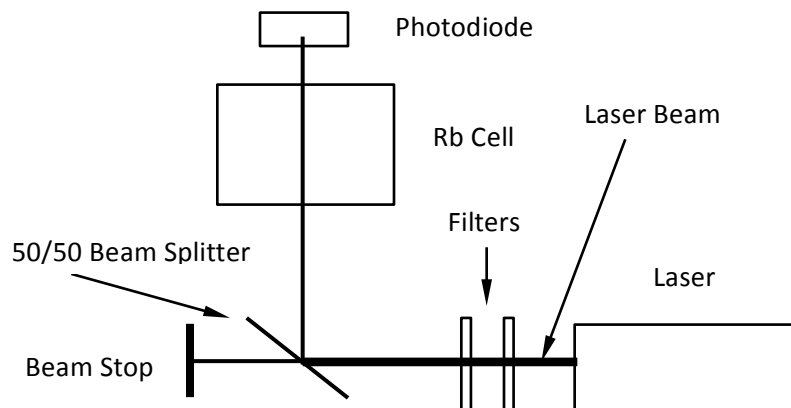


Figure 4. Simple configuration for observing absorption resonances in Rb atoms.

Whenever the laser's frequency coincides with an absorption resonance for Rb, the signal reaching the photodiode detector is attenuated. The laser frequency is selected by adjusting the angle of a grating on the output. This angle is manipulated with a piezoelectric, which is a material that mechanically deforms with the application of a voltage. It is possible to continually sweep the laser frequency by applying a triangular waveform to the piezoelectric with a ramp generator. This waveform and the output from the photodiode can be observed with an oscilloscope, and an example of these data is shown in Figure 5. One-half cycle of the signal from the ramp generator that drives the piezoelectric is displayed by the top trace.

Questions: Why is it only necessary to display one-half cycle? If the length of the piezoelectric is proportional to the applied voltage, how does the laser frequency change with time for this ramp voltage, assume changes in the grating angle is very small? The bottom trace shows the signal from the photodiode as a function of time, which is related to the laser's frequency. The photodiode signal is inverted so absorption resonances for Rb atoms appear as peaks in the trace. Mode hops are shown in the lower scope trace as discontinuous jumps in the signal from the photodiode. These are undesirable because they can obscure spectral features of interest. The next section will discuss how to eliminate mode hopping and create a trace showing only the absorption features.

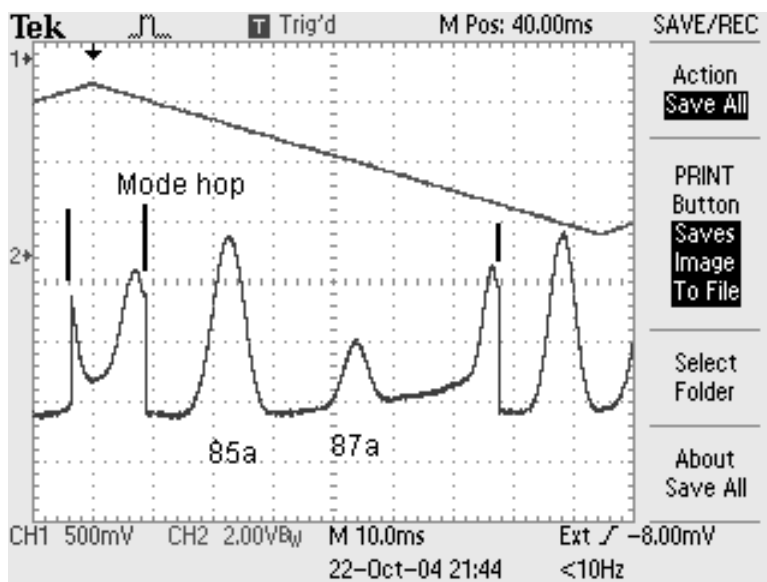


Figure 5. Oscilloscope trace showing Rb absorption resonances.

2.2 Rb Absorption Spectrum without Mode Hopping

As discussed in Appendix 1 in the DSL Supplement, simultaneous modulation of the piezoelectric and laser current will eliminate mode hopping. In this section you will configure the optics as indicated in Figure 4 above to create a scan with no mode hops. Attach the 50/50 (not the 10/90) beam splitter and its holder to the optics bench as indicated, and adjust its position so that one of the laser beams travels through the Rb cell and into the photodiode detector. Once the beam splitter is in position, use the IR viewing card to locate the laser beam and make final adjustments on the alignment of the beam splitter. It may be helpful to turn off the room lights. Adjust the beam intensity with neutral density filters to give the best results. (All three plastic and the glass neutral density filters may not be needed.)

Appendix 3 in the DSL Supplement describes the initial configuration and startup procedure for the laser and associated equipment. **It is important to follow this procedure to avoid damaging the equipment.** Adjust the ramp generator and piezoelectric controls so that the piezoelectric drive voltage resembles the lower scope trace (trace #1) in Figure 6 below. Make sure to set the zero for trace #1 as indicated in the figure. Configure the photodiode and controller as indicated below:

Photodiode gain = 333 K Ω

Cell temperature = 45 °C

Laser diode current = 54.0 mA

DC offset = 1.95 V (as read from dial on piezoelectric module)

Current modulation attenuator = 1

Starting with this configuration, adjust the control settings above as required until the scan looks similar to that in Figure 3. Save your scan to a flash drive following the instructions in Appendix 4 in the DSL Supplement. **All of your scans must include a date and time stamp to receive credit.**

The lower trace shows one-half cycle of the ramp generator. In the upper trace you can clearly see the four absorption peaks. However, the slope resulting from the current modulation may be obscuring some features of the absorption spectrum. In the next section we will learn how to subtract out the background slope, leaving a flat trace containing the four absorption peaks.

2.3 Background Subtraction

The laser control module can be configured to subtract out the background electronically using a signal from a second photodiode. To do this, the optics must be reconfigured as shown in Figure 7. For this configuration, the beam stop is replaced with a second photodiode

(photodiode #2), and the signal from this photodiode will be subtracted from that coming from photodiode #1. You will need to adjust the new 50/50 beam splitter and photodiodes to optimize detection of the two laser signals. Note that in this section and those that follow, the position and height of the photodiode detectors is critical to optimize the detection of the laser signals. The IR viewing card can be used to view the beam so that the components can be aligned for optimal signal. Once optimized, configure the cables from the controller as indicated in Figure 8.

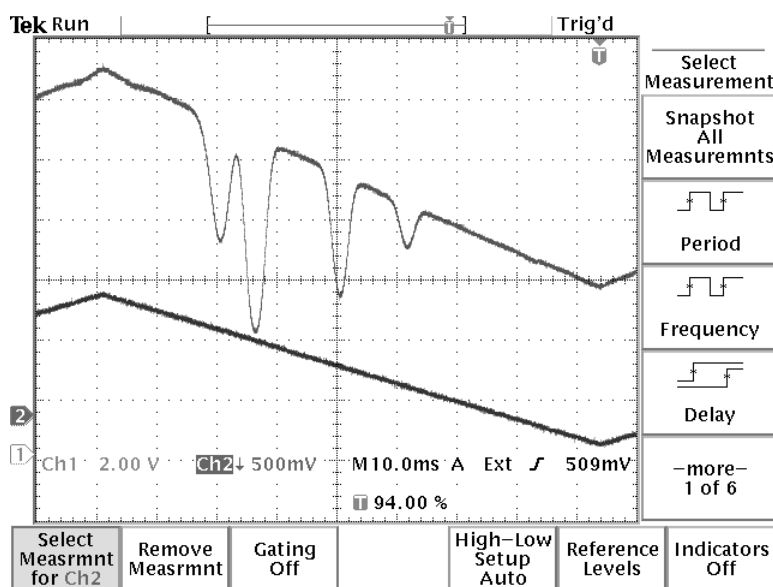


Figure 6. Oscilloscope scan without mode hops.

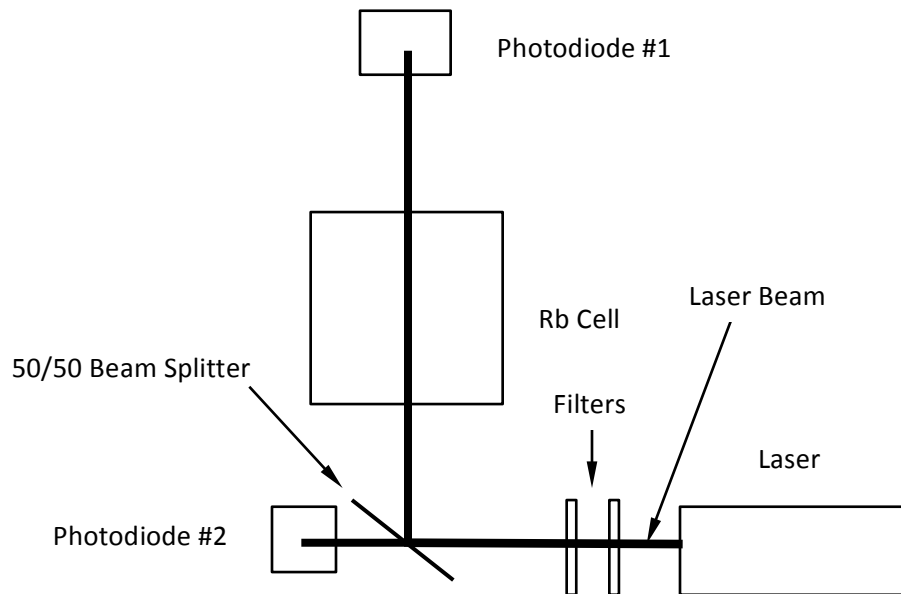


Figure 7. Optical system for subtracting two laser signals.

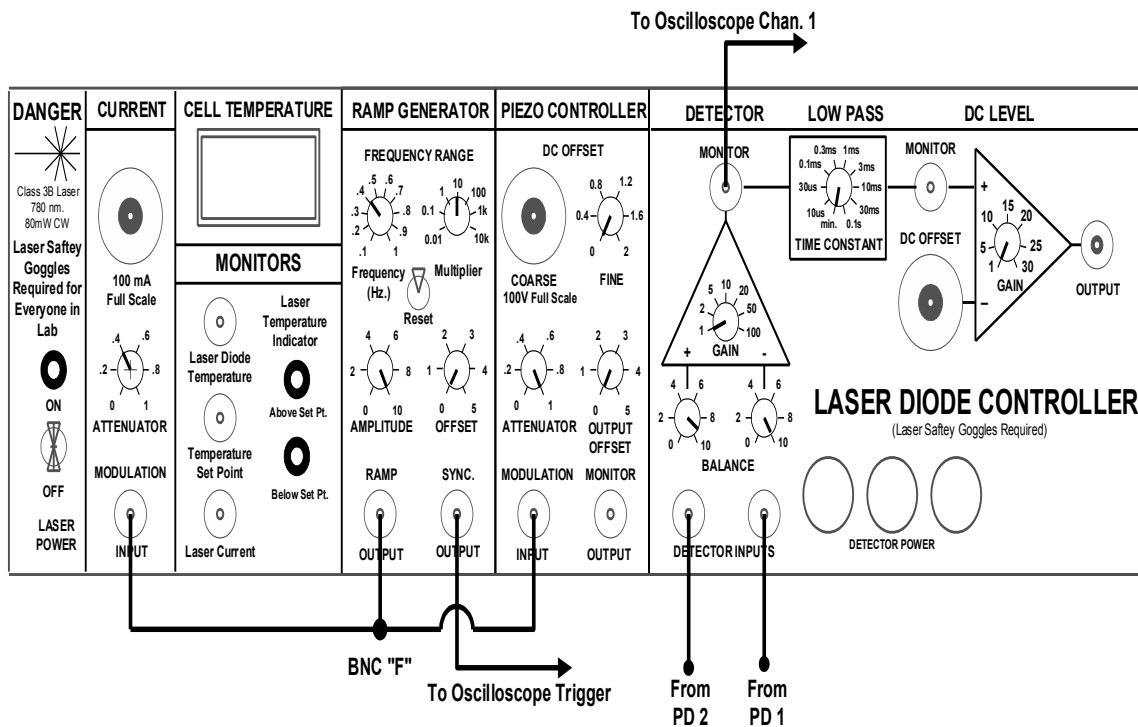


Figure 8. Controller Modules showing connection for two photodiode detectors.

Use the other scope channel to monitor the piezoelectric voltage. Once all of the cables are connected, configure the controller settings as indicated below:

Photodiode #1 gain = 1 M Ω
 Photodiode #2 gain = 3.3 M Ω
 Cell temperature = 45 $^{\circ}$ C
 Laser diode current = 51 mA (as read from dial)
 DC Offset = 8 V (as read from dial)
 Current Modulation Attenuator = 1
 Plus balance = 1
 Minus balance = 0.4
 Detector gain = 1

Starting with these control settings, adjust them as needed until you create a scan similar to the one in Figure 9. Note that the frequency of the ramp generator has been increased slightly so that the turning points exceed the range of the scope display. Again adjust the type and number of neutral density filters to optimize the scan, and save the scan to a flash drive. This scan clearly shows a spectrum with a flat background, no mode hops and four absorption resonances. These absorption peaks are Doppler broadened, and this obscures finer structure in the spectrum. *Question: Approximately, what is the Doppler-broadened linewidth?* In the next section you will learn a technique that removes this broadening to study the hyperfine structure of Rb.

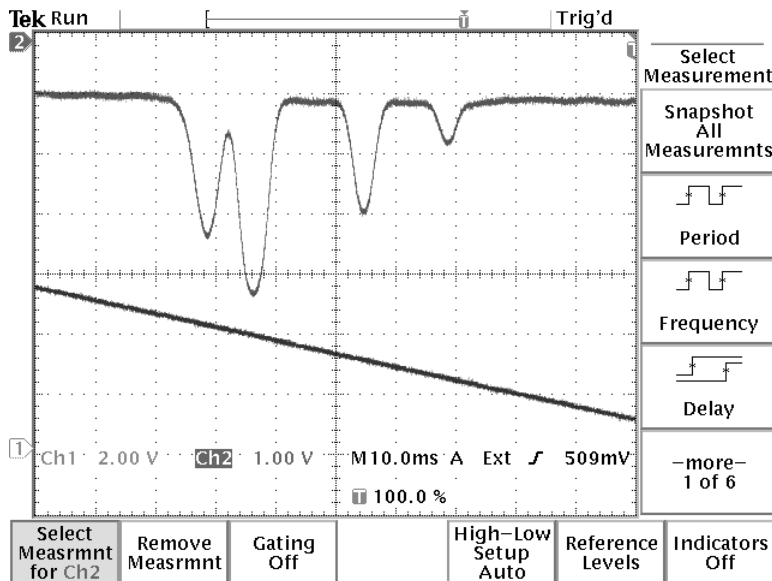


Figure 9. Oscilloscope scan of the spectra with the background subtracted.

3. Hyperfine Structure of Rubidium

3.1 Saturation Absorption

The energy separation between the levels that constitute the hyperfine structure is smaller than the Doppler-broadened line widths, so a phenomenon called saturation absorption will be used to remove the Doppler emission from the spectra. Begin by reading Appendix 5 in the DSL Supplement, which describes the theory of saturated absorption spectroscopy (SAS). As you know, the frequency of a photon depends on the relative velocity of the source and receiver – a phenomenon known as the Doppler Effect. With SAS, the only atoms that simultaneously interact with both the pump and probe beams are those with a zero thermal velocity relative to the laser because the pump and probe beams approach the atoms from opposite directions. For atoms with a single excited state, the pump beam excites most of these atoms into their excited state, prohibiting them from absorbing an additional photon from the probe beam. So for these atoms, there is virtually no absorption from the probe beam. This *absence of absorption* appears as a narrow spike in the Doppler broadened absorption peak. For atoms with multiple excited states, multiple spikes appear in the spectrum. When those spikes are isolated, they constitute the spectrum in the absence of Doppler broadening.

To perform SAS measurement, the optics must be configured according to the instructions in Appendix 6 in the DSL Supplement. Most of the layout is similar to what was used in the previous section, so you only need to add the extra components and align everything. When adjusting the optical components for optimum performance, it is useful to display both photodiode signals on the oscilloscope screen. The controls should be set to observe the Doppler

broadened absorption peaks in each channel with the magnitudes of the two signals as close as possible. When these signals are subtracted, the saturated absorption signal should be displayed with minimal Doppler broadening. After optimizing the optical alignment, the controller should be configured with the following settings:

Laser diode current = 52.0 mA (as read from the dial)
 Current attenuator = 0.8
 Ramp generator frequency = 0.55 Hz
 Ramp generator multiplier = 10
 Ramp generator amplitude = 10
 Piezoelectric DC offset = 18.1 V (as read from the dial)
 Piezoelectric fine = 0
 Piezoelectric attenuator = 1

A final optimization of the signal can be done with small adjustments of the scope settings and photodiode gain. To analyze the hyperfine structure, a frequency calibration for the horizontal axis is needed. This calibration has already been done; however it is dependent on the controller settings, so it is only valid if the controller settings above are used.

When the probe signal is subtracted from the pump signal, a saturated absorption spectrum like that shown in Figure 10 should be observed. Notice that each Doppler-broadened resonance is replaced with a series of very narrow peaks, which represent the hyperfine structure of Rb. There are four groups of absorption peaks that are broadened at the base. This is caused by imperfect subtraction of the signals from photodiodes #1 and #2, and also power broadening from the intensity of the laser beam. Power broadening can be minimized by reducing the intensity of the laser beam with the plastic neutral density filters. If the signals are very noisy, use the “Acquire” function on the oscilloscope to average the signal. Each group of peaks can be expanded as shown in Figure 11 for the analysis. Save the scans to a flash drive.

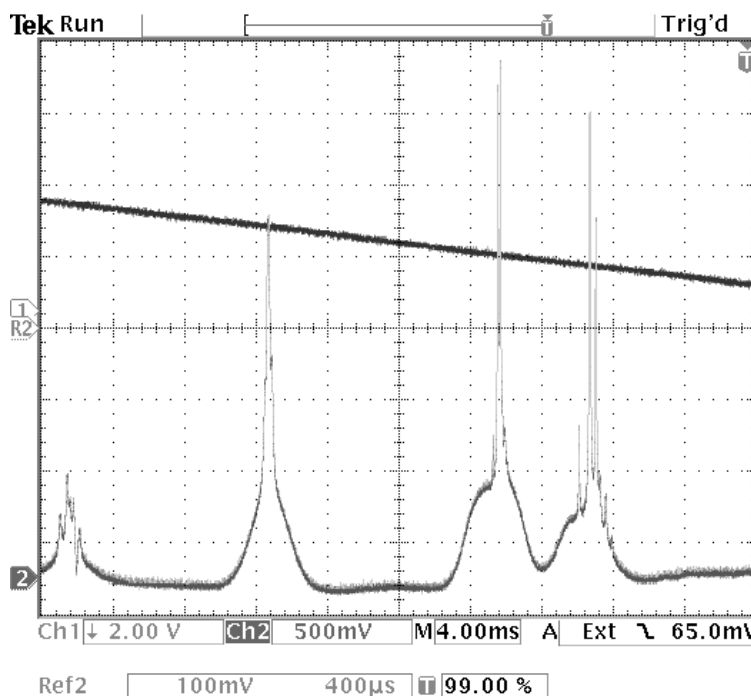


Figure 10. Scan showing the four groups of absorption peaks with the hyperfine structure within each peak.

With the calibration discussed in Section 3.2, determine the ground state splitting for each isotope of Rb. Express your results in MHz. Identify and quantify any sources of error. From the expanded scans of the four groups of peaks, identify as many energy levels as possible. Draw a quantitative energy-level diagram that coincides with the transitions observed in the spectra.

3.2 Laser Frequency Calibration

In the scans above, the horizontal axis is time, and for the absorption spectra, the time axis is proportional to the frequency of the laser. For the analysis of the hyperfine structure, you need to know the proportionality constant. This can be determined using a Fabry-Perot interferometer. This is an optical cavity that functions as a filter, allowing only certain frequencies to pass through. If a swept frequency enters a Fabry-Perot interferometer, a series of peaks is observed at the output with an oscilloscope representing the transmission of light at specific frequencies,

and the separation in frequency between these peaks is determined from the length of the cavity (20.0 ± 0.2 cm) and the speed of light. By measuring the time between the fringes on the oscilloscope, a frequency calibration can be determined. In principle, you could calibrate your apparatus, but to save time, this was already performed. With the controller setting above, the calibration is 234 MHz/ms. Remember, this is only valid when the controller setting above are used. Notice that this calibration only provides the frequency difference between two spectral features in a scan, not an absolute frequency. (e.g., you cannot use a Fabry-Perot interferometer to determine the absolute frequency of the laser light.) However, this is not a problem because for spectroscopy, you only need to know the energies of the levels relative to the ground state. *Questions: What is the equation for the separation in frequency between the peaks on the output of the Fabry-Perot interferometer? Why does the ramp generator frequency affect the calibration?*

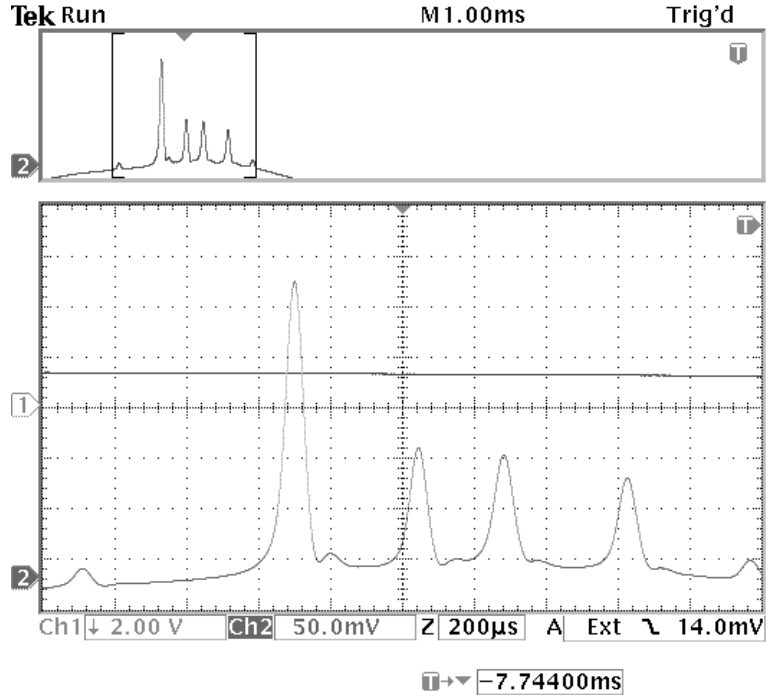


Figure 11. Expanded scan showing the hyperfine structure within one absorption peak.

4. The Zeeman Effect

Above you learned that when the electrons interact with a magnetic field from the nucleus, the atomic levels are further split, leading to the hyperfine structure. As one might expect, an externally applied magnetic field would have a similar effect on the atomic levels, and this phenomenon is called the Zeeman Effect. When a magnetic moment μ interacts with an external magnetic field B , the perturbation to the atomic energy levels is given by

$$\Delta E = -\mu \cdot B$$

At low fields where the Zeeman energy is small compared to the hyperfine interaction, the energy levels are characterized by F and F_z , and the Zeeman splitting to first order is

$$\Delta E_{\text{weak}} = g_F \mu_B m_F B$$

where $g_F \approx g_J \frac{F(F+1) - I(I+1) + J(J+1)}{2F(F+1)}$, g_J is the Landé g-factor, μ_B is the Bohr magneton and $m_F = -F, F+1, \dots, F$ is the quantum number for F_z . Transitions between these levels are determined by the selection rules $\Delta m_F = \pm 1$ or 0.

At higher fields where the Zeeman energy exceeds the hyperfine coupling, but is still smaller than the spin-orbit coupling, the levels are eigenstates of J and J_z , and

$$\Delta E_{\text{strong}} \approx g_J \mu_B m_J B$$

where $m_J = -J, J+1, \dots, J$ is the quantum number for J_z . Eventually, even this expression breaks down. The Zeeman splitting for the $^2S_{1/2}$ and $^2P_{3/2}$ levels of ^{87}Rb where numerically calculated for magnetic fields up to 500 G, and the results of these calculations are shown in Figure 12. The hyperfine coupling for the $^2S_{1/2}$ level is strong enough that the weak-field limit is valid over the whole field range of the calculation; however, the hyperfine coupling is much smaller for the $^2P_{3/2}$ level, a transition from the weak-field to the strong field limit occurs

somewhere around 100 G. Since the magnet on your apparatus is limited to ~ 100 G, you can assume the weak-field limit holds for both levels.

Set up the apparatus for saturated absorption so that you are able to observe the hyperfine structure. The magnetic field will be provided by a Helmholtz coil surrounding the Rb cell and a current-limited power supply. **Never exceed 3 A, or you may damage the coils.** The calibration for the magnet is given by $B = \frac{0.9 \times N \times I}{R}$. For this expression, B is the magnetic field in Gauss, $N = 320$ is the turns per side, I is the current in amps and $R = 8.74$ cm is the average coil radius in centimeters. Measure the spectrum at 1.0A, 1.5A, 2.0A, 2.5A and 3.0A. Try to identify the transitions in the spectra and plot energy splittings as a function of field. From these data, determine g_F . Remember to include an uncertainty and a discussion of the sources of error.

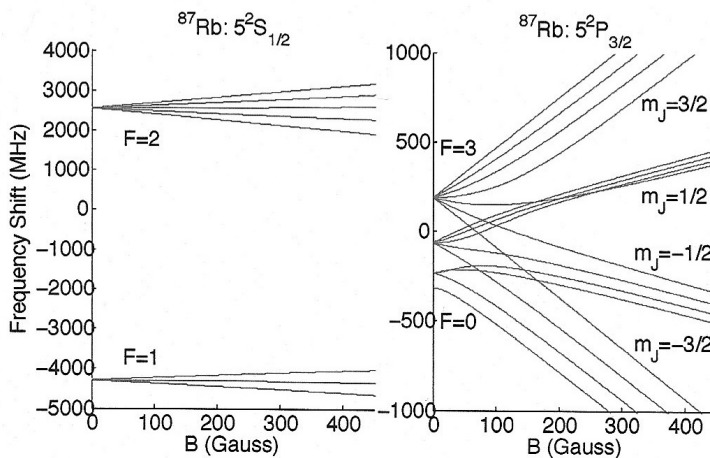


Figure 12. Numerically calculated hyperfine-Zeeman frequency shifts for the $^2S_{1/2}$ (left) and $^2P_{3/2}$ (right) states in ^{87}Rb . Notice that for the $^2P_{3/2}$ state, the low-field levels are characterized by m_F , while m_J is used for the high-field states.

5. References

1. Most undergraduate textbooks on quantum mechanics have a good introduction to atomic physics. Three examples are Stephen Gasiorowicz, *Quantum Physics* (Wiley, 2003), David McIntyre, Corinne Manogue and Janet Tate, *Quantum Mechanics* (Pearson, 2013) and Robert Eisberg and Robert Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles* (Wiley, 1985).
2. T. W. Hänsch, A. L. Schawlow and G. W. Series, "The Spectrum of Atomic Hydrogen", *Scientific American* **240**, 94 (March 1979).
3. C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, *Atom-Photon Interactions* (Wiley, 1992).
4. G. Herzberg, *Atomic Spectra and Atomic Structure* (Dover, 2010).
5. P. Milonni and J. Eberly, *Lasers* (Wiley, 1988).