Saturated Absorption Spectroscopy

George R. Welch

31 January, 2021

1 Introduction

The purpose of this laboratory is to introduce the student to saturated absoprtion spectroscopy. This is a technique that allows spectroscopic transitions that are inhomogeneously broadend by Doppler averaging to be observed with frequency resolution close to their natural linewidths.

In the process students will observe absorption spectra showing Doppler broadening and splitting of the spectrum due to nuclear hyperfine structure and isotope shift.

2 Background

The system we will use is the "D2 transition" in rubidium vapor. This is the transition between the $5S_{1/2}$ ground state (that is, principal quantum number $n = 5$, orbital angular momentum $L = 0$, and total electron angular momentum $J = 1/2$) and the upper fine-structure component $5P_{3/2}$ of the first excited state (orbital angular momentum $L = 1$ and total electron angular momentum $J = 3/2$).

The spectrum is complicated by the rubidium nucleus in two ways. First, the nuclear spin couples with the electron spin to split the ground and excited states (the splitting is caused by the interaction of the nuclear magnetic moment with that of the elctron). Second, natural rubidum consists of two isotopes: Rb-85 and Rb-87. These nuclei have different nuclear spins. Naturally occuring rubidium consists of 72% Rb-85 with nuclear spin $I = 5/2$ and 28% Rb-87 with $I = 3/2$. An enormous amount of detailed information about this transition in Rb-85 and Rb-87 can be found in refs [1] and [2] respectively. The energy levels resulting from coupling these spins are shown on the following two pages.

At room temperature, the Doppler width of an isolated transition in rubidium is about 500 MHz. An important thing to notice as you look at these diagrams is that the upper state splittings are smaller than the Doppler width and will not be resolved in absorption spectroscopy. In order to resolve these transitions, a technique is needed to eliminate Doppler broadening. Saturated absorption spectroscopy is an example of such a technique.

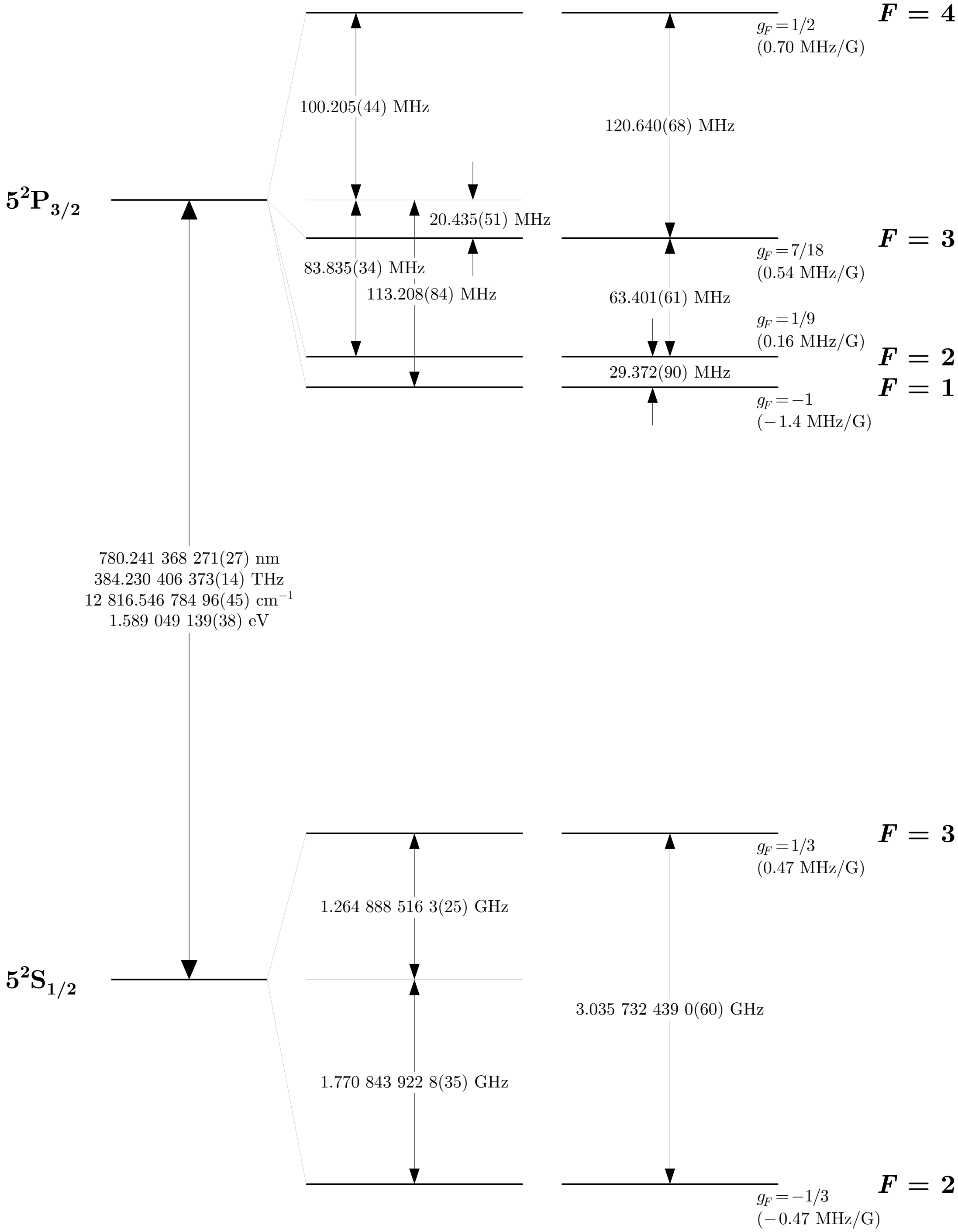


Figure 1: This figure is from Steck [1] and shows rubidium 85 D2 transition hyperfine structure, with frequency splittings between the hyperfine energy levels. The ground and excited-state state values are taken from references cited in [1]. The relative hyperfine shifts are shown to scale within each hyperfine manifold (but visual spacings should not be compared between manifolds or to the optical splitting). The approximate Landé g_{JF}-factors for each level are also given, with the corresponding Zeeman splittings between adjacent magnetic sublevels.

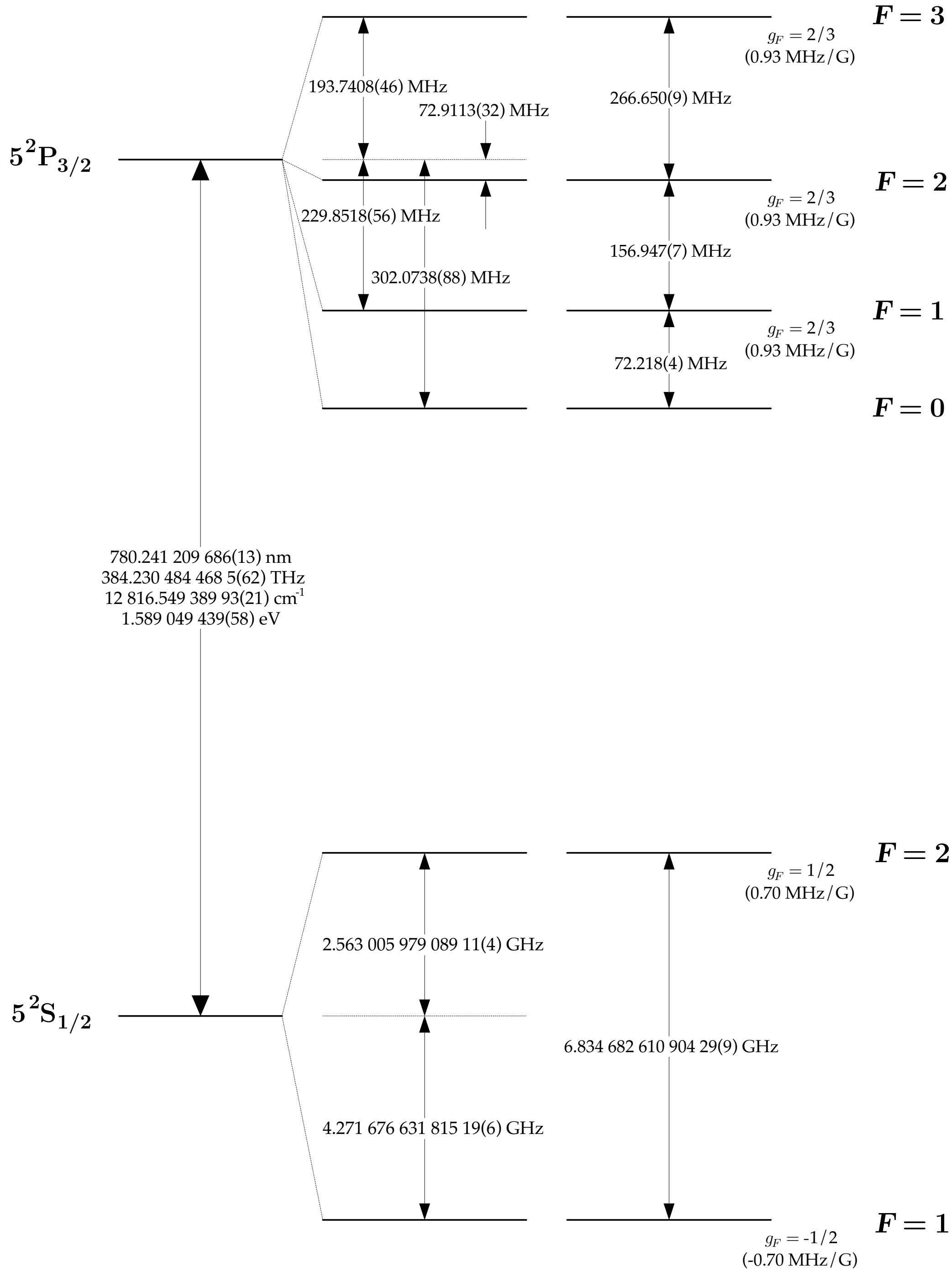


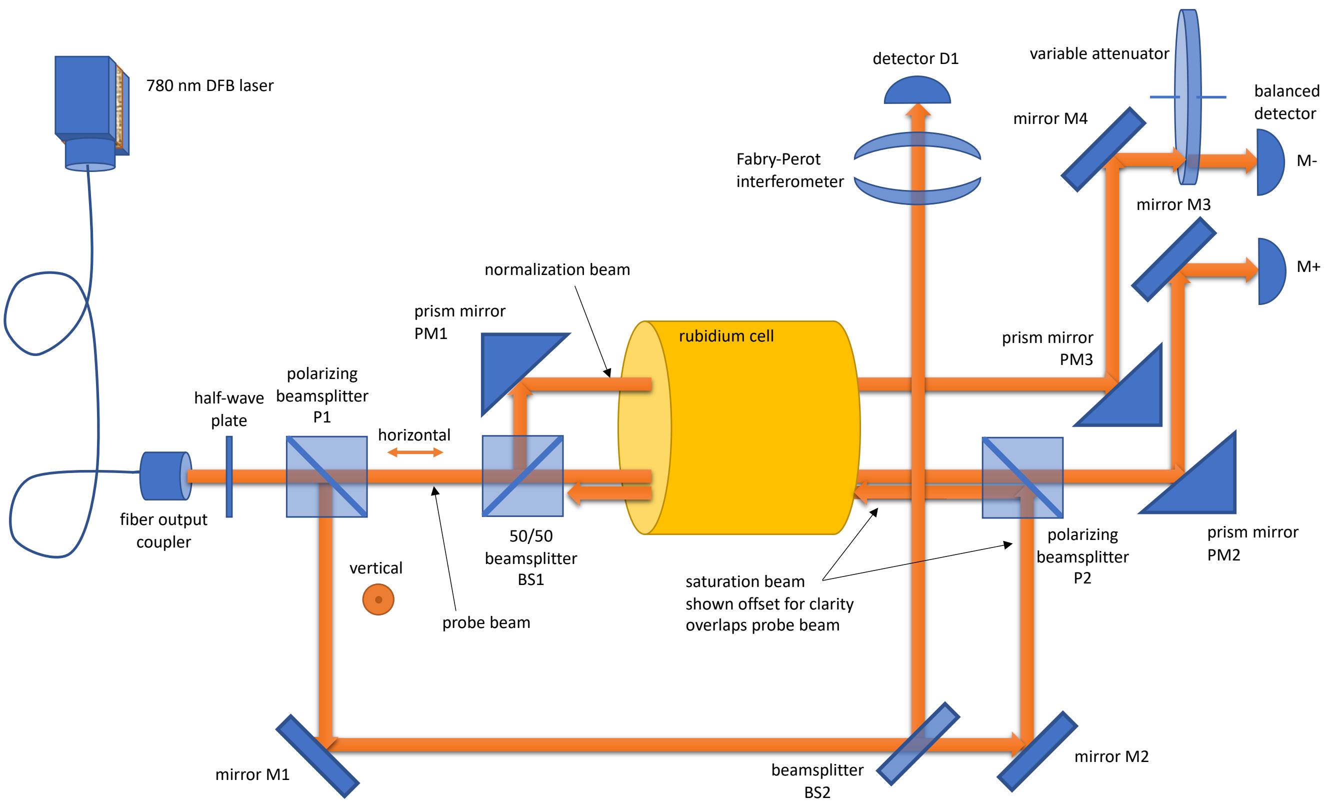
Figure 2: This figure is from Steck [2] and shows rubidium-87 D2 transition hyperfine structure, with frequency splittings between the hyperfine energy levels. The ground and excited-state values are taken from references cited in [2]. The approximate Landé g_{JF}-factors for each level are also given, with the corresponding Zeeman splittings between adjacent magnetic sublevels.

3 Study

Before you begin, study this experimental schematic and see if you can identify the various components on the optical breadboard. Be super careful! Prisms P1 and P2 are not clamped in place; they are held only by gravity. Don't touch them!

If you are confused about the correspondence between items in this figure and on the actual setup, just ask! We are here to help.

On the optical breadboard, not shown in the figure, there should be a white card blocking the laser beam after mirror M2.



4 Fabry-Perot interferometer

The Fabry-Perot interferometer serves as our frequency reference while the laser is scanning. This kind of interfermeter was invented by Claude Fabre, professor emeritus at the Sorbonne University and member of the Kastler-Brossel Laboratory of Sorbonne University, École normale supérieure and Collège de France, and H. Ross Perot, an American Business magnate who ran unsuccessfully for president of the United Sates in 1992, losing to Bill Clinton.

A Fabry-Perot interferometer consists of two mirrors which reflect most of the light entering the interferometer, unless the wavelength of the light matches a resonance condition: $m\lambda = 2l$ where l is the separation of the mirrors, m is an integer, and λ is the wavelength of the light. When λ is such that this resonance condition is filled, the two mirrors transmit the light.

Thus, as the frequency of the laser is tuned the Fabry-Perot transmits periodically, with transmission peaks separated by $\Delta f = c/2l$. For our interferometer, the transmission peaks are separated by $\Delta f = 1.5$ GHz.

To learn more, you could just Google “Fabry Perot interferometer” without the quotes. The Wikipedia page is okay.

5 Procedure

5.1 Turn on heater and detectors

The ThorLabs TC200 temperature controller is to gently heat the rubidium cell from its room temperature to about 30°C. If the TC200 is not already turned on, then turn it on: press “Enable” and complain to your intructor that the temperature controller was not on.

Turn on the detector behind the Fabry-Perot interferometer and also the balanced detector at the end of the laser beam paths. Turn on the oscilloscope.

5.2 Turn on laser

5.2.1 Temperature Controller

First turn on the ThorLabs TED200C temperature controller power. This device changes the temperature of the laser diode with a thermoelectric device. It is the “course” frequency adjustment for the laser.

Don’t change any settings on this device except those described here!

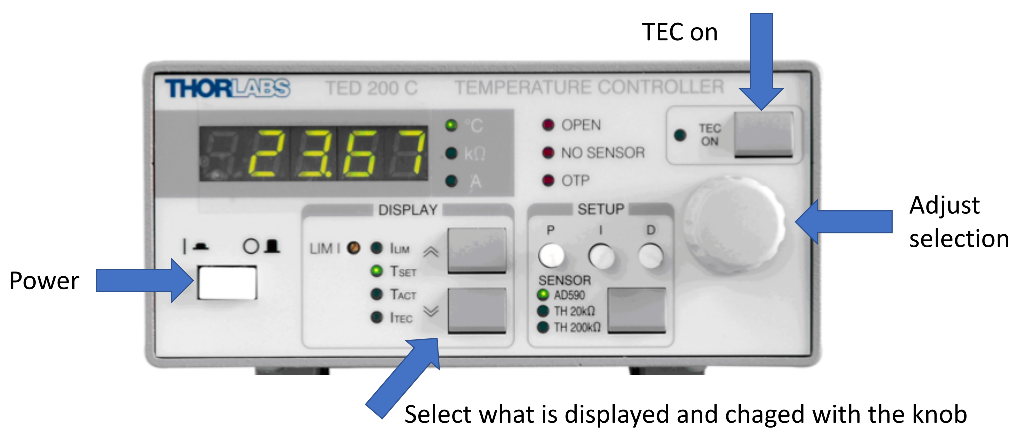


Figure 3: ThorLabs TED-200C temperature controller.

The laser does not have a fancy temperature sensor, so the temperature controller works with a thermistor in the laser. A thermistor is just a resistor whose resistance varries with temperture in a known way. You will find a chart showing resistance as a function of temperature for the ranges of interest. For room temperature, the resistance is about 11 kΩ and this is what should be shown for T_{act}.

Use the front panel buttons to change the reading to T_{set}. This shows the reading that the controller is currently programmed to. Set this to 10.000 kΩ. Then switch the display back to T_{act}. Now press the "TEC ON" button and you should see the thermistor value change to the set value of 10 kΩ.

5.2.2 Laser Controller

This device controls the current through the laser. Increasing the current increases the laser power and also increases the laser frequency. This is your "fine" frequency adjustment.

Don't change any settings on this device except those described here!

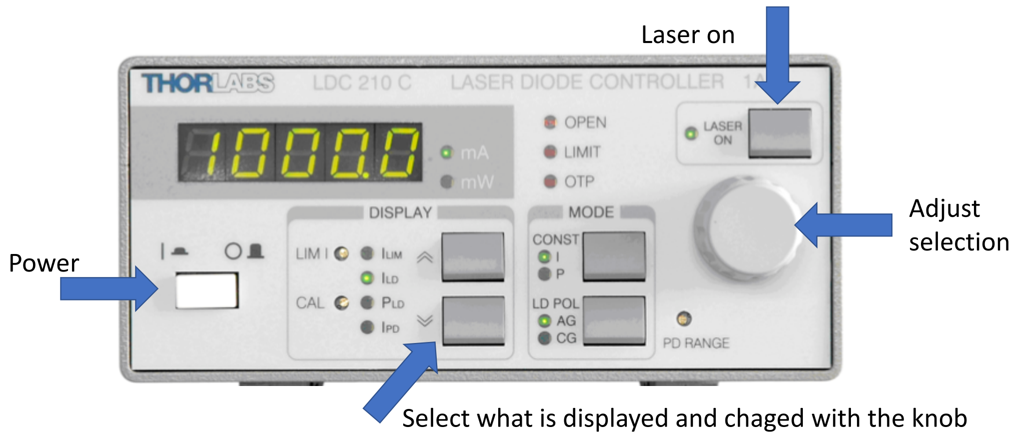


Figure 4: ThorLabs LDC-200C laser diode controller.

Turn on the LDC202C power. Adjust the current knob so that it is fully counter-clockwise. Now press the "Laser On" button. It should show approximately zero current. Slowly turn the current knob until the current is about 70 mA. It is better for the laser not to change the current suddenly by a large amount. You don't have to take forever, but take a few seconds. The laser is now emitting a few mW of laser power in a single frequency with about 1 MHz of bandwidth!

You might see the thermistor value on the temperature controller fluctuate as you bring the current up. This is normal because the laser is heating.

Carefully place the yellow part of the IR card in the path of the laser beam coming out of the fiber mount. You will see a spot where the infra-red laser beam hits the card.

5.3 Modulate laser frequency

The ThorLabs LDC202C has a modulation input in the back. This is connected to the Siglent SDG 1032X function generator. We want to program this function generator to output a ramp signal so that the current set by the LDC202C is modulated up and down a bit. This is what "sweeps" the laser frequency back and forth around a set value.

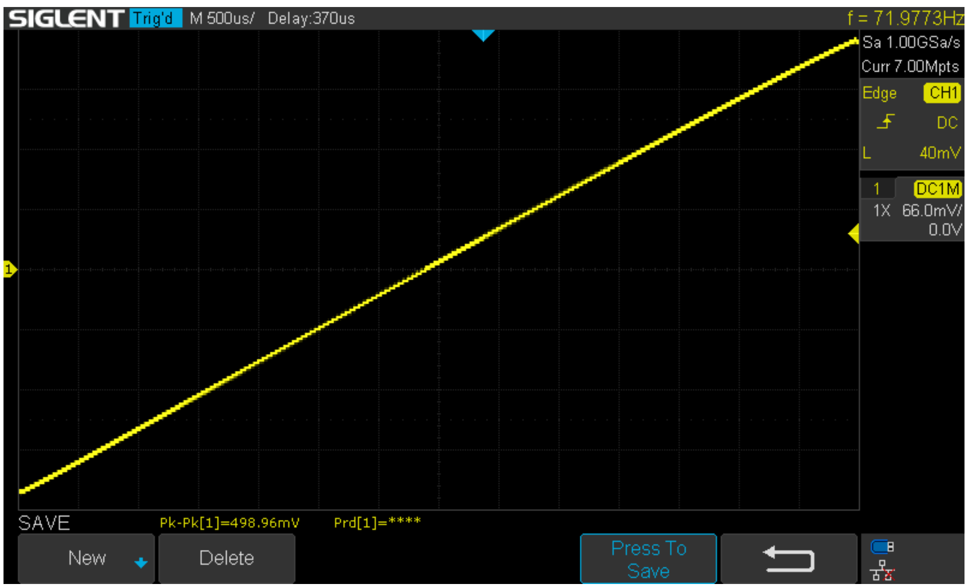
Turn on the SDG 1032X. Now press the "Waveforms" button and select "Ramp". Now adjust the frequency to 70 Hz. Next set the amplitude to 500 mVpp. Make sure the offset is zero. Press the button underneath amplitude again so that amplitude is selected, as you will be changing this.

Now press the "Output" button on channel 1. The function generator is now feeding a ramp into the laser diode controller, and the laser current is being modulated up and down around 70 mA.

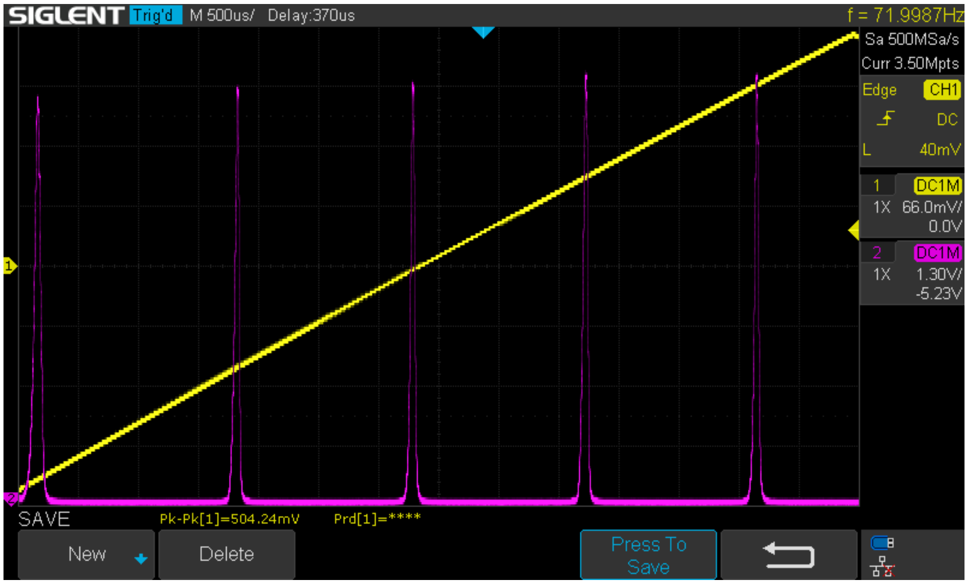
5.4 Adjust the Oscilloscope

As you make connections to the oscilloscope, make sure your cables do not disturb the optical alignment. These are stiff, thick cables and it is easy to accidentally knock things about with them.

Connect the output of the function generator to input 1 on the scope. Adjust the scope to trigger off this input with rising slope and zero level. Now adjust the time-base of the scope to 500 μs per division, and then make small adjustments to the frequency of the function generator and the horizontal position on the scope so that so that you get one half period of the ramp shown on the scope.

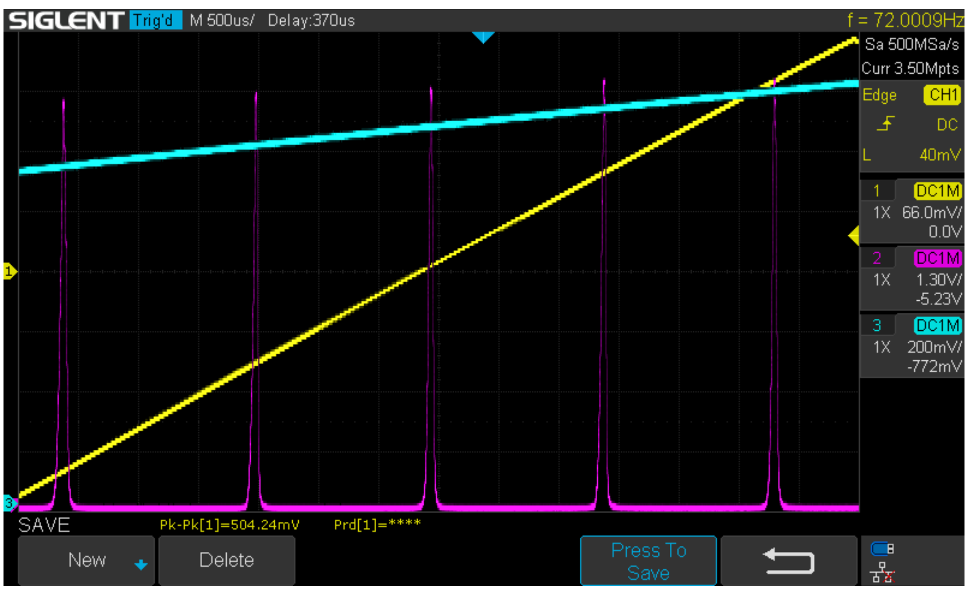


Now connect the output of the detector behind the Fabry-Perot interferometer to input 2 of the scope. You should see the transmission peaks as the laser sweeps through resonance with the Fabry-Perot. Adjust the gain and vertical offset of this input so that the peaks are nicely displayed.



This figure shows about 5 transmission peaks. Their separation is 1.5 GHz, so you know the laser is scanning about 7 GHz.

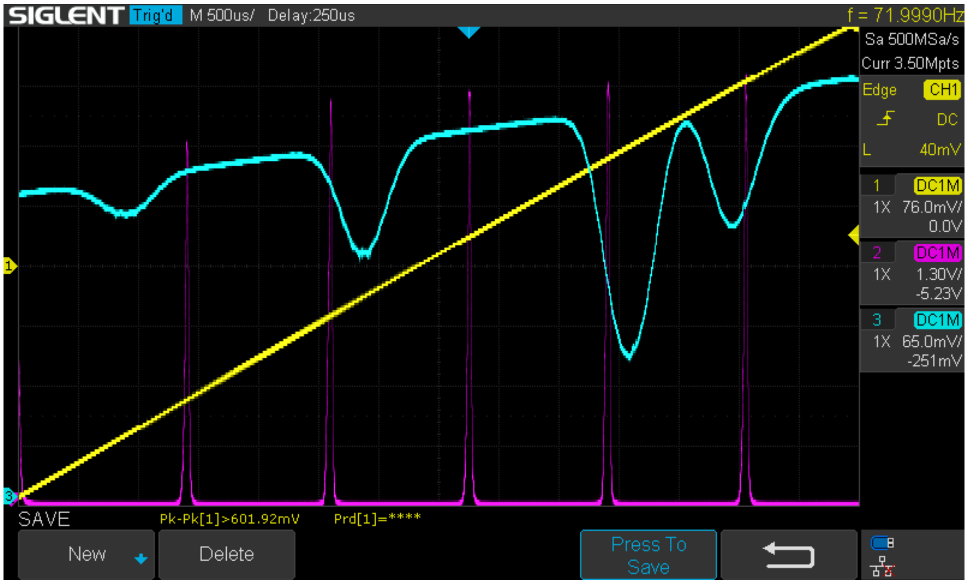
Now connect the "Monitor −" output of the balanced detector to channel 3 of the scope. A vertical gain of 200 mV/division is probably okay, and set the vertical position so that zero is at the very bottom. You should now see a signal that changes in value a bit as the laser scans from left to right. This is the effect of the laser current (which is what we are scanning) causing the laser power to change somewhat as you scan.



6 Data Taking

You are now ready to look for the transition in rubidium. Slowly adjust the T_{set} knob on the ThorLabs TED200C temperature controller until the thermistor value is about 7.07 kΩ.

For fun, you can watch the Fabry-Perot resonances shift rapidly as the center frequency of the laser changes. Once you are near this temperature, you may need to adjust it slightly, but you should be able to find all four Doppler-broadened absorption peaks of the rubidium D2 ($5S_{1/2} \rightarrow 5P_{3/2}$) line.

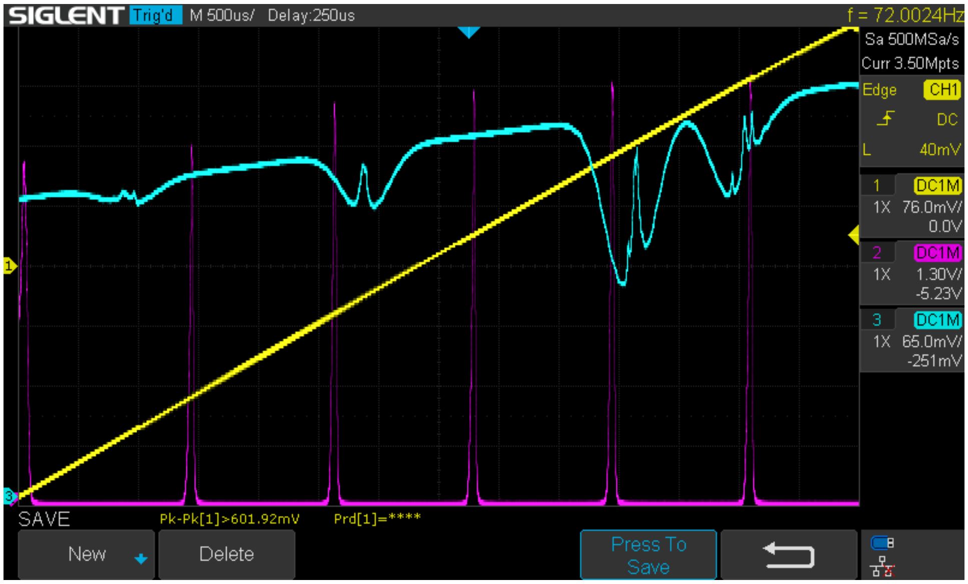


Adjust the scope until the spectrum is as well displayed as possible. Feel free to fine-tune the amplitude of the laser scan (that is, the ramp output from the function generator).

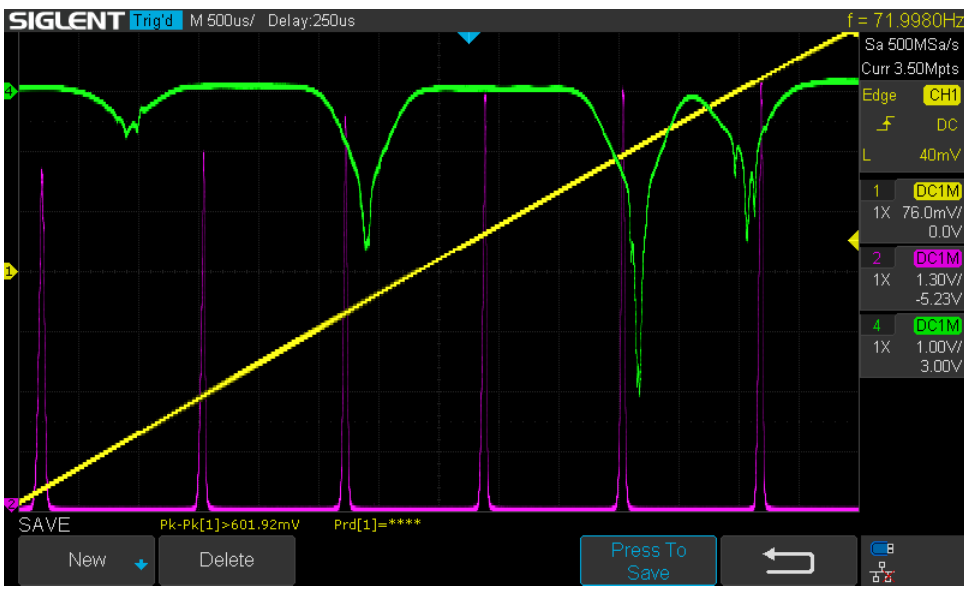
Recorde these data! You will use this to determine the hyperfine splitting of these transitions. Make any adjustments you like and record as many scans as you like. To record data, use the “Save/Recall” button on the scope. You can save the data to a flash drive in any format you like.

7 Saturated Absorption

Now remove the card that is blocking the saturation beam. You should now see saturation peaks in the absorption resonances that are much narrower than the Doppler width. I recommend recording a good spectrum before you make any adjustments, but do feel free to make small changes to the overlap of the saturation beam with the probe beam using mirror mount M2 and prism mount P2.

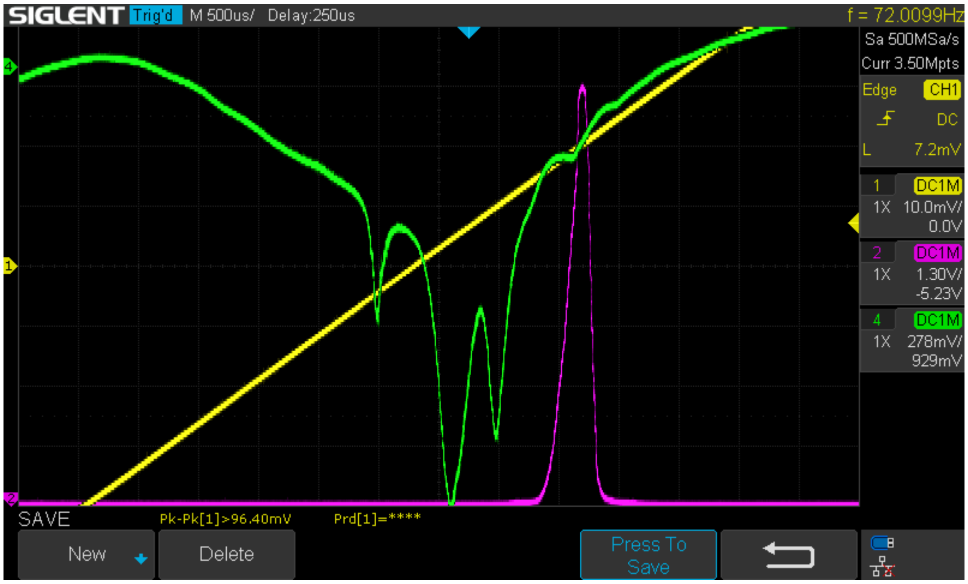


Now connect the "RF output" from the balanced detector to input channel 4 of the scope. I suggest setting the vertical gain to about 2 Volts per division and the vertical position near the top of the screen. Adjust the attenuator wheel so that the level is zero away from the resonances. You should now have a pure saturated absorption specturm. (I have removed trace 3 to avoid clutter.) Record these data.

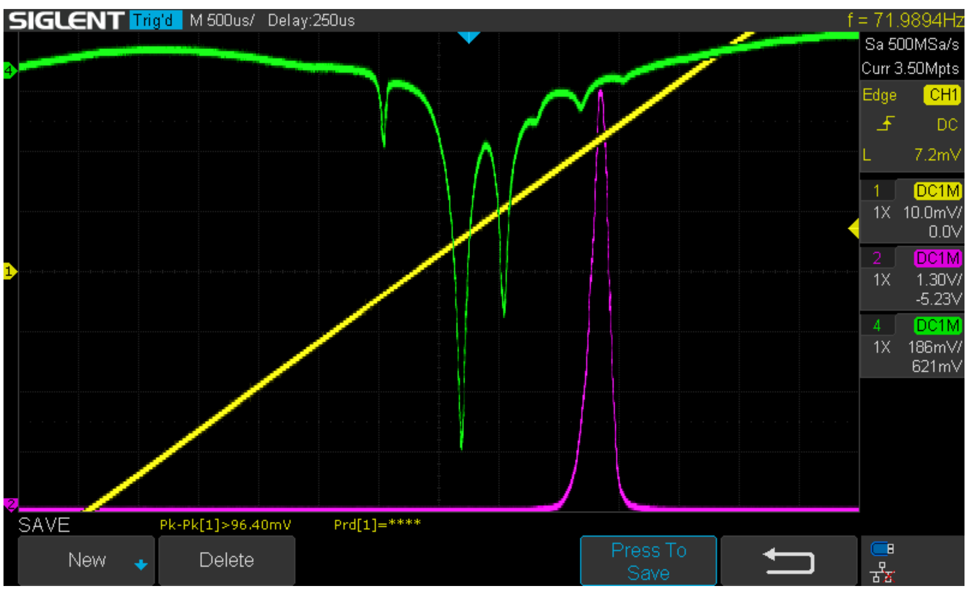


Now you can "zero in" on the various hyperfine components by making tiny offsets to the temperature and lowering the amplitude of the function generator.

Record these data. For example, here is the 87Rb F=3 peak:



These saturated absorption peaks are power broadened. See if you can get them to be narrower by adjusting the overlap of the saturation beam with the probe beam, again using mirror M3 and prism mount P3.



What are all these resonances? Explain them!

8 What to write up

Make sure you read this before you leave the lab! You may realize you need to write something down that you forgot.

Your report should be as complete as you can make it, but as a minimum you need the following deliverables:

- Identify the four peaks in the absorption spectrum.
- Measure the ground state hyperfine splitting of Rb-85 and Rb-87. Of course your measurements will be a bit crude, but there is no reason you cannot get one good significant figure, or perhaps a bit better.
- Try to explain the saturated absorption peaks. Which ones correspond to transitions to upper-level hyperfine components, and which are something else? And what might that something be.

References

[1] Daniel A. Steck, “Rubidium 85 D Line Data,” available online at http://steck.us/alkalidata (revision 2.2.1, 21 November 2019).

[2] Daniel A. Steck, “Rubidium 87 D Line Data,” available online at http://steck.us/alkalidata (revision 2.2.1, 21 November 2019).