Using Electric Fields to Produce and Observe Optical Pumping Effects in Rubidium Gas (^{85}Rb and ^{87}Rb)

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Abstract
Experimentation was conducted on optically pumped rubidium to determine the optimal magnetic field settings to obtain obvious dimming results. Detailed explanations of equipment used, and photos of equipment setup are included in the methods section. Results were obtained and briefly explained for the first experiment. Experimentation was also conducted to obtain and analyze Zeeman resonant levels in a limited capacity, with more analysis room given to that experiment. Copious amounts of data were collected and stored for deeper analysis at a later date. Graphical analysis was conducted using MATLAB to illustrate some of the striking changes in the Zeeman levels with changes to applied RF voltage and frequency. Three Zeeman levels were definitively observed with a possible fourth one being noted but cut off in data collection.

Introduction
Optical pumping is an experimental method to examine magnetic field interaction on atomic energy sublevels.[i] Light travels from a rubidium discharge lamp through a series of polarizers and a quarter waveplate to enter a specially constructed cell as right-handed polarized light. The cell is filled with more rubidium buffered with neon and is kept at 50°C.[ii] The resultant light is focused through lenses onto a photodetector and transmitted as a measurement of voltage.

Magnetic fields interact with the rubidium chamber to affect the amount of light absorbed by the rubidium atoms, thereby affecting the resultant throughput of light. Because radio waves are electromagnetic in nature, these can also be applied to change the Zeeman levels. Optical pumping involves saturating the target atoms so that they can no longer absorb light and then changing their local magnetic field so that they are able to move to energy levels permitting absorption once again.

Methods

The following materials were used:
2 linear polarizers in rotatable mounts (50mm diameter)
2 plano-convex lenses (50mm diameter and focal length)
4 GB FAT-formatted USB stick
Black angle banana plug to point tester (for voltmeter)
Detector amplifier input cable
Detector amplifier output cable
Digital thermometer
Dip needle
Draping cloth to prevent extraneous light from entering photodetector
Function waveform generator
Google Drive
Interference filter (50mm diameter)
MATLAB R2019a
OnePlus 6T camera
Optical rail
Photodiode preamp photon detector
Preamp power cable
Quarter waveplate in rotatable mount (50mm diameter)
Recorder output cable
Red angle banana plug to point tester (for voltmeter)
RF output cable
Rubidium discharge lamp
Tektronix TBS 2000 Series Digital Oscilloscope
Temperature and heater thermocouple cable with two-pronged thermocouple connector and two-pronged heater connector
Temperature controller
Vertical sweep field banana clips (red and black split connectors)
Vertical sweep field banana clips (red and black split connectors)
Voltmeter
Windows 10 laptop

Equipment was set up in accordance with manual instructions. All optical components were aligned with the rail in the same horizontal direction as the local ambient magnetic field (mostly from Earth). All connections were made with the controller per the manual. Connections were occasionally made from the controller monitor connections to a voltmeter in DC measuring modes when required. Setup is illustrated in figures 1 through 15.

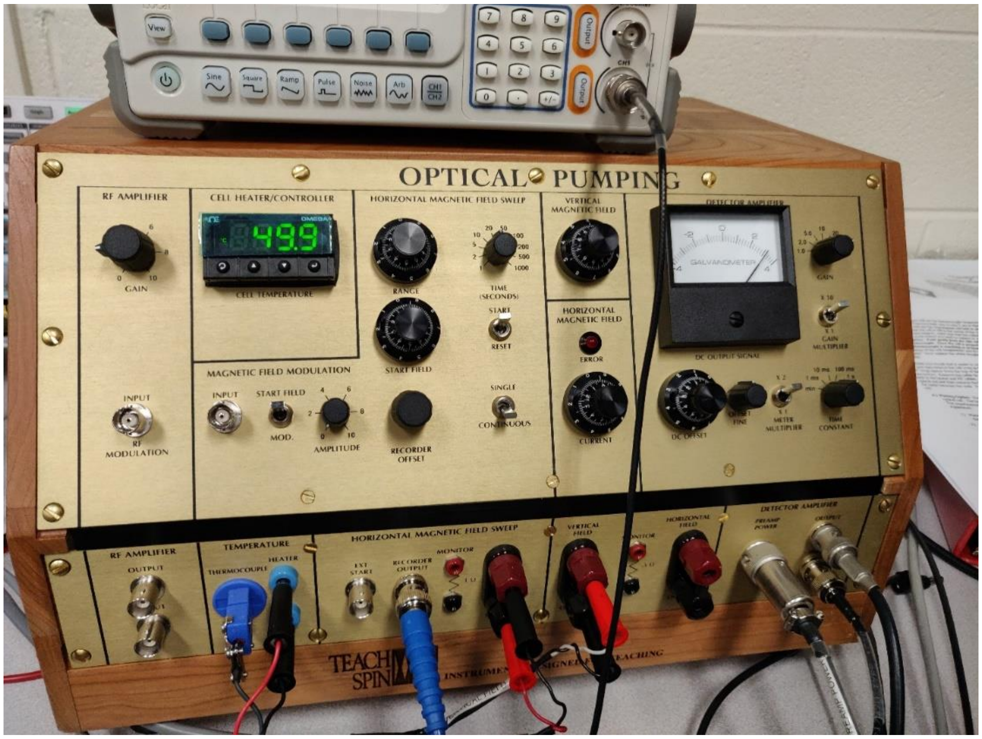

Figure 1: Optical Pumping Controller

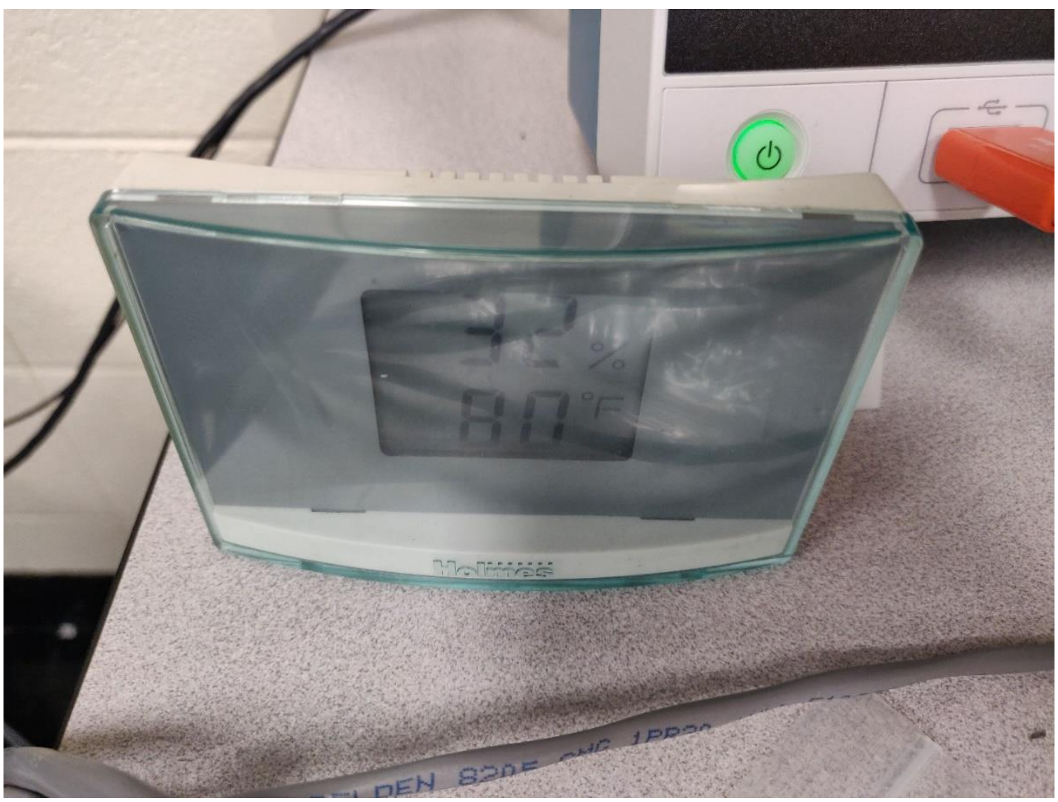
Figure 2: Ambient Temperature and Humidity Monitoring

Figure 3: Optical Rail Standard Setup Showing Horizontal Magnetic Field Alignment (No Cover)

Figure 4: Optical Rail Measurement between Photodetector and Focusing Lens with Draping Cloth Visible in Background

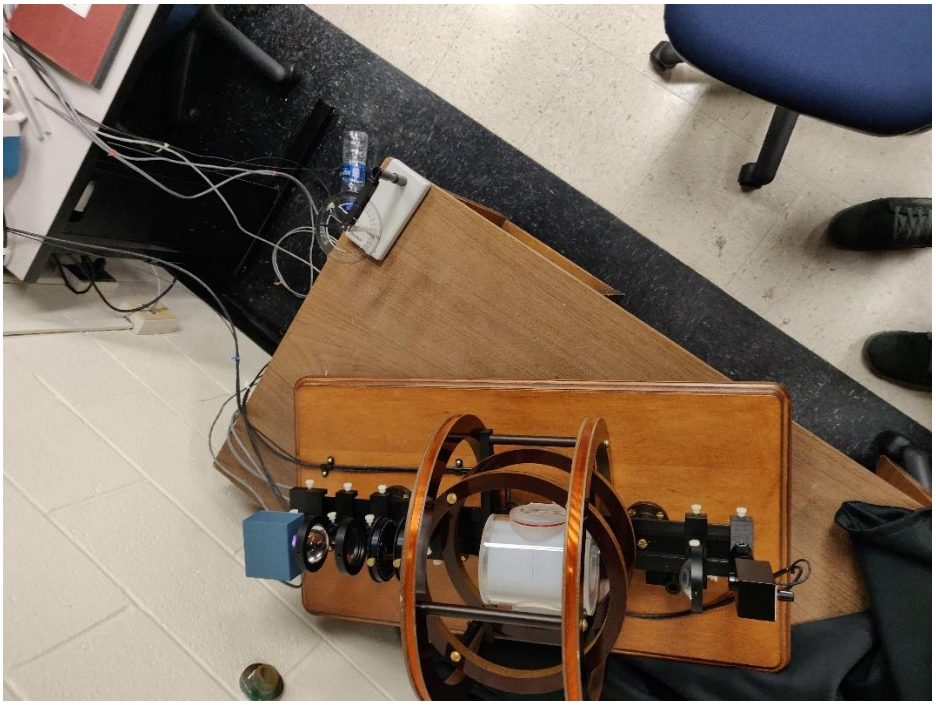

Figure 5: Overhead View of Optical Rail

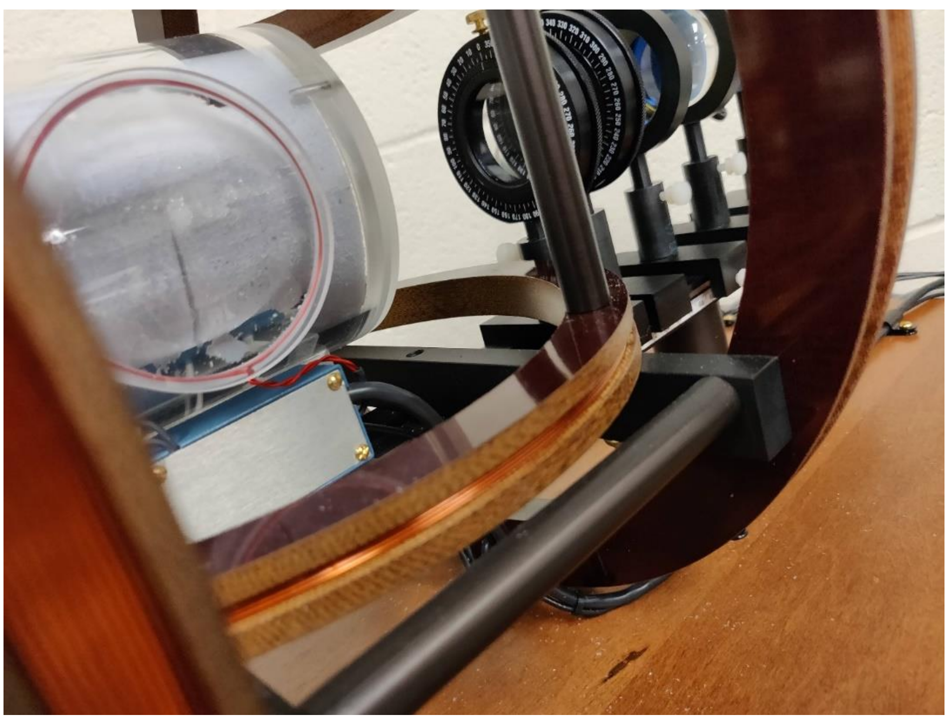

Figure 6: Rubidium Optical Pumping Chamber inside Helmholtz Coils

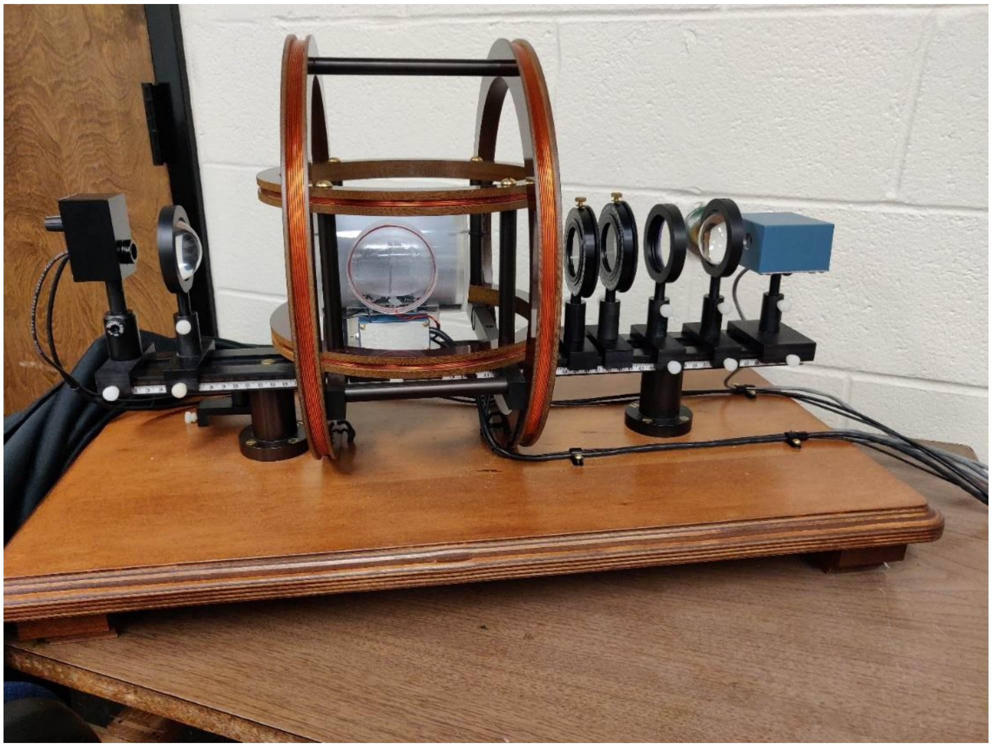

Figure 7: Optical Rail Setup (Scale Readable)

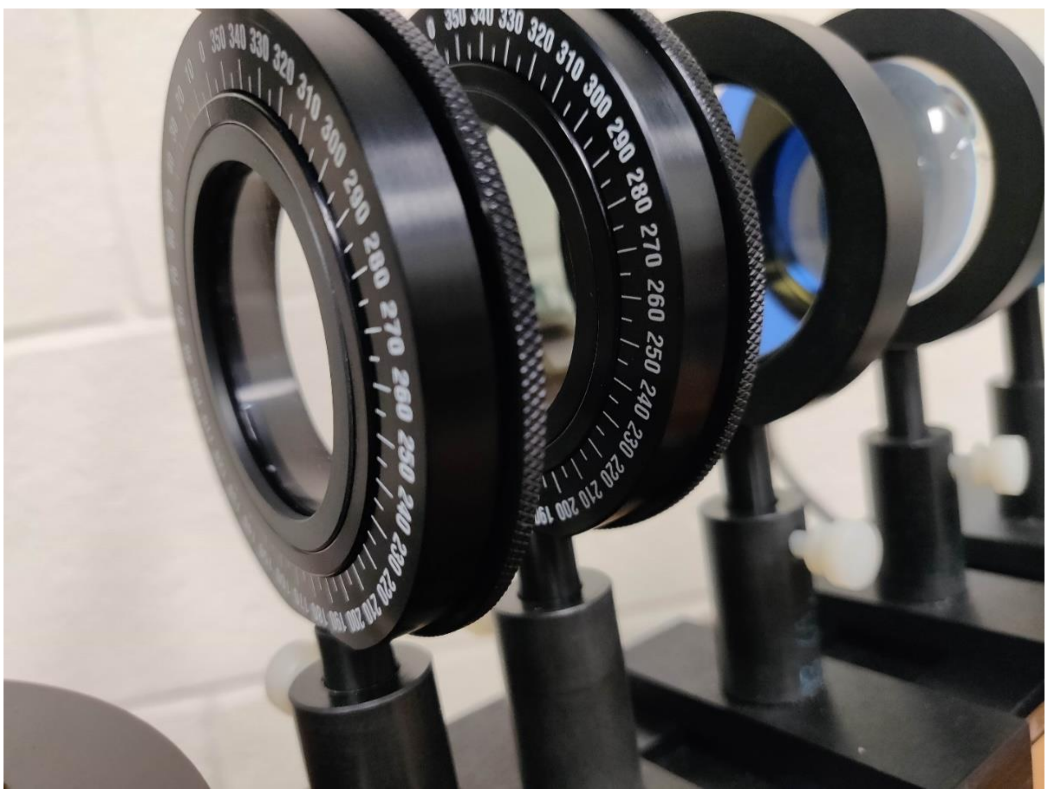

Figure 8: Closeup of Lens and Polarizers after Rubidium Discharge Lamp

Figure 9: View into the Optical Pumping Chamber

Figure 10: View after Rubidium Discharge Lamp before Entering Optical Pumping Chamber

Figure 11: Voltmeter without Sensor Cables Attached


Figure 12: Draping Cloth (Also Mentioned as “Cover” and “Drop Cloth”)

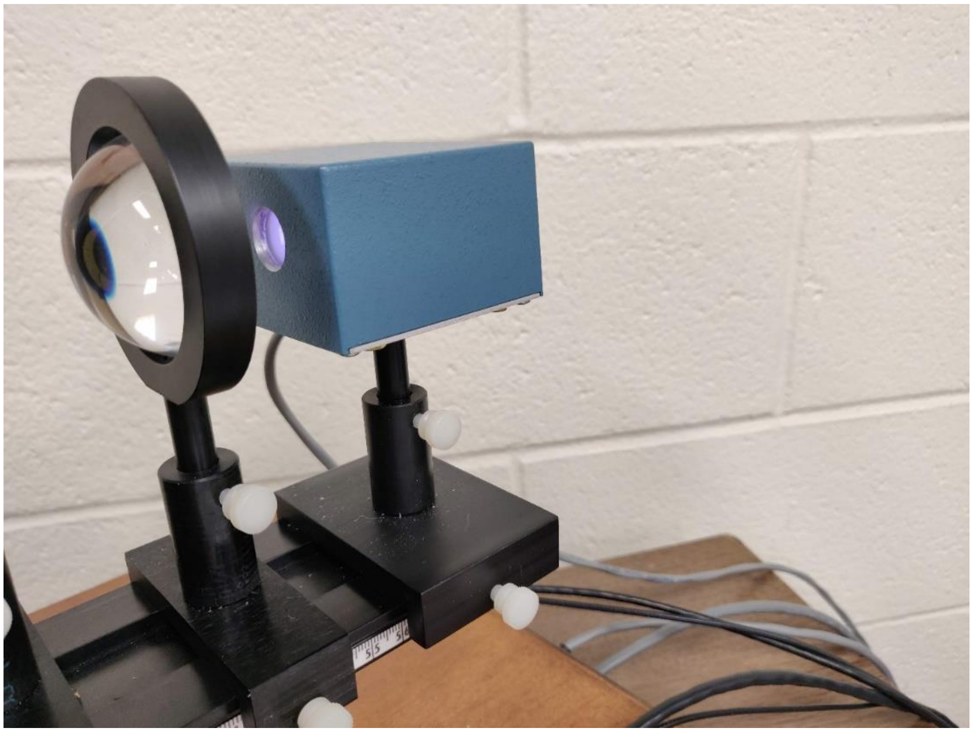

Figure 13: Rubidium Discharge Lamp Powered On and Emitting Photons

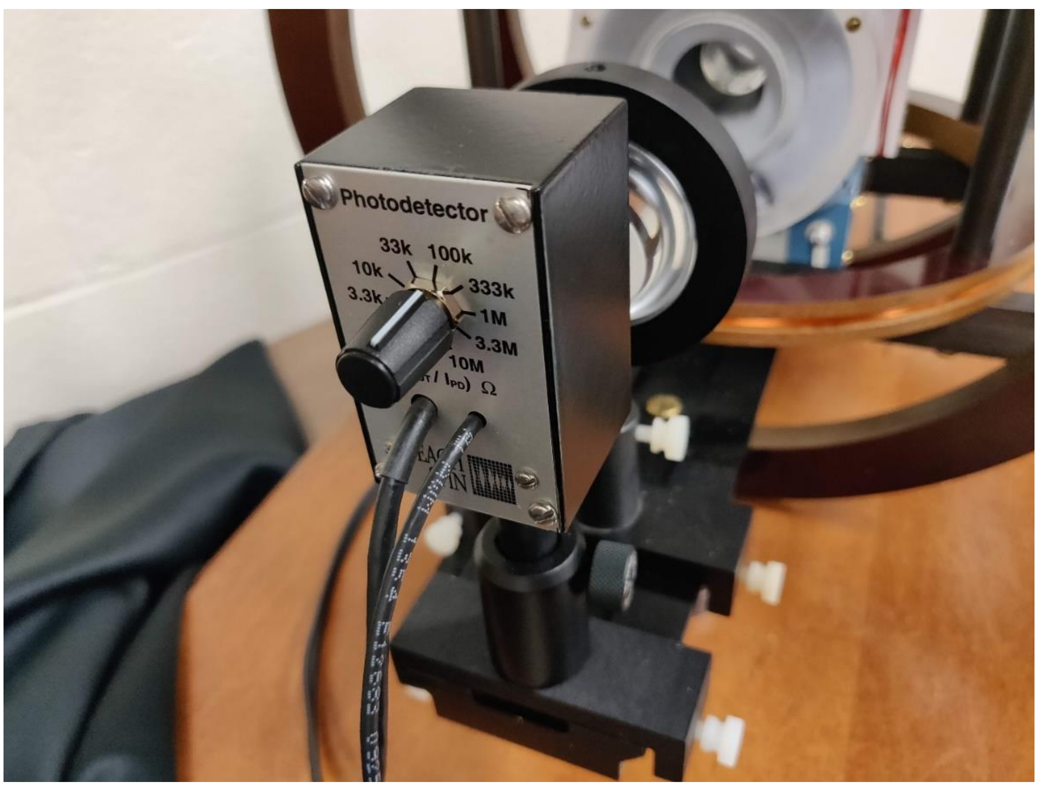

Figure 14: Photodetector Settings

Figure 15: RF Signal Generator

The initial setup was complicated by apparently loose thermocouple connections causing the readout to fluctuate wildly. Reseating the connection fixed the problem. Most measurements were made in x-y mode on the oscilloscope, although some diagnostic reviews were made in y-t mode along with some later data collections in experiment 2. Data was exported as oscilloscope screen grabs and CSV data collections from CH1 and CH2, along with timestamps. The resulting CSV files from x-y mode and y-t mode are the same. Equipment was turned on for at least 30 minutes to allow the temperature to warm up and stabilize before beginning experimentation. While data was being collected and observed, the drop cloth was placed over the experimental apparatus to minimize extraneous photons interfering with the optical pumping chamber and photodetector.

Two experiments were run to observe the effects of optical pumping. The first experiment was run to determine the horizontal sweep field settings necessary to cause the steepest and narrowest dip in signal, corresponding to optically pumped Rubidium atoms, before resetting to pre-pumped transparency values (Figures 16 & 17). The second experiment was run to determine the Zeeman resonances. Both experiments together generated 11 pages of lab notes, 790 KB of screengrabs, 2.37 GB of oscilloscope data, and 377 MB of still and video imagery. A third experiment measuring temperature in Kelvin against resulting voltage was attempted but was unsuccessful because of both recording the wrong output signal and not allowing time for the temperature to settle. The third experiment is therefore not included in this report.

Figure 16: Optically Pumped Rubidium Atoms Dimming Photon Throughput to Photodetector

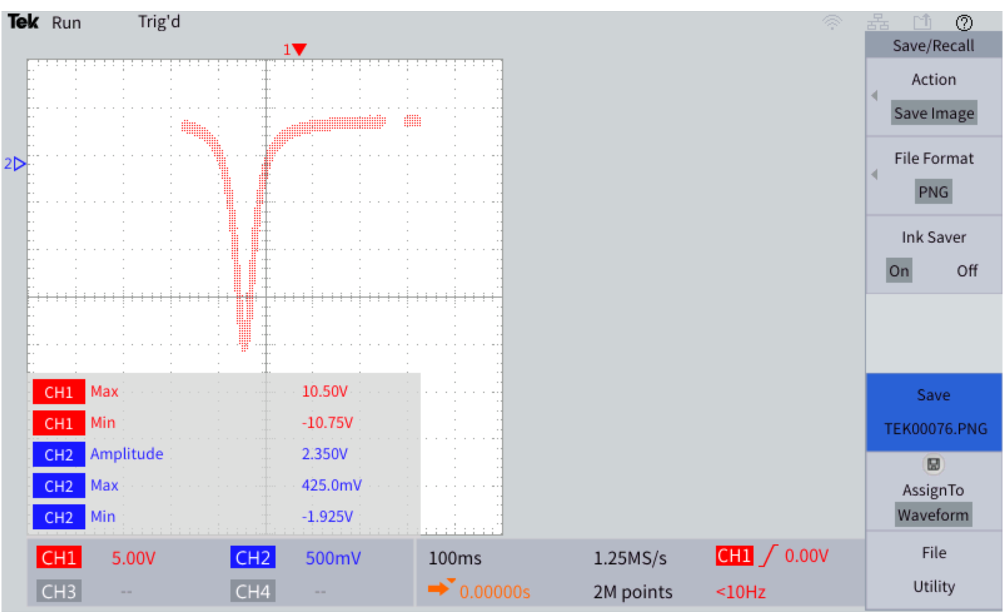

Figure 17: Screengrab of Optically Pumped Rubidium Atoms

The first experiment involved setting the vertical magnetic field to sweep while keeping the horizontal magnetic field stable. Readouts on the Galvanometer were obtained and two different types of displays on the x-y oscilloscope readout were observed for the same data. The horizontal field setting was chosen to result in the steepest drop and return in photon transmission.

The second experiment required the equipment to be set up in the same manner as it was finished in the first experiment. The vertical magnetic field was set to 2.42 dA $\pm$ 0.01 dA with the horizontal magnetic field sweeping from null to 0.985 V $\pm$ 0.001 V in 2 seconds (precision not found on the dial). A radio frequency (RF) was then applied. Changes were made in the RF voltage and RF frequency before observations were made. With the waveform generator set to 150.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz, the voltage was changed from 1 to 20 Volts in 1 Volt $\pm$ 0.001 V increments. With the voltage set to 5 V ± 0.001 V, the frequency was then swept in 10 kHz $\pm 1 \cdot 10^{-5}$ kHz increments from 150.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz to 210.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz and then from 300.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz to 1000.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz in 100 kHz ± $1 \cdot 10^{-5}$ kHz increments. Additional stops were made at the frequencies shown in Table 1. All measurements were conducted with the thermistor set to maintain 47.0 $°C \pm$ 0.5 $°C$ in the optical pumping chamber. The temperature was chosen because it was closest to the manual's suggestion to maintain a temperature of 320K. The ambient temperature was measured at 75 $°F \pm 1\ °F$ with a humidity of 26% $\pm$ 1% to 27% ± 1%. Additional information can be found from the PDF of the lab manual in the data collection file at (bit.ly/Optical_Pumping_2019).

Graphs were made of the CSV files using MATLAB because Excel was unable to handle the large number of data points being generated.

RF Frequency in kHz $\pm \mathbf{1 \cdot 10^{-5}}$ kHz
303.00000
300.30000
400.20000
500.20000
1000.10000

Table 1: Additional Tested Radio Frequencies

Sweep coil parameters
Mean radius ($\bar{R}$) = 0.1639 m $\pm$ 0.0001 m
11 turns (N) on each side
I is current in amps

Sample Calculations
B(Gauss) = $8.991 \cdot 10^{-3} \frac{I \cdot N}{\bar{R}}$
Resonant Frequencies $\nu = g_F \mu_0 B/h$

$${}^{\mu_0}/_{h} = 1.3996\ MHz/gauss$$

$$\text{h} \equiv 6.62607015 \cdot 10^{-34}\,\frac{J}{H}$$

$$\mu_0 = h * 13996\,\frac{MHz}{gauss}$$

L ≡ angular momentum (not properly defined in the handbook and therefore defined here as 1)

$$S = \frac{1}{2} = J = \kappa = L$$

$$F = 1\ or\ 2$$

$$g_J \equiv 2$$

$$g_F = g_j\,\frac{F(F+1) + J(J+1) - \kappa(\kappa+1)}{2F(F+1)} = \begin{cases} 2\,\dfrac{1(1+1) + \frac{1}{2}\left(\frac{1}{2}+1\right) - \frac{1}{2}\left(\frac{1}{2}+1\right)}{2(1)(1+1)} = \dfrac{3}{2} \\ 2\,\dfrac{2(2+1) + \frac{1}{2}\left(\frac{1}{2}+1\right) - \frac{1}{2}\left(\frac{1}{2}+1\right)}{2(2)(2+1)} = 1 \end{cases}$$

Results

Resonance levels for the frequency generator set to 150.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz and 5 V ± 0.001 V are shown in Figure 18 and Figure 19. Figure 19 is CSV File 10 analyzed. All CSV files include 2 million data points based on oscilloscope collection. Using the same procedures, a slight change in intensity is evident going from 5 to 8 volts in Figure 20. A more pronounced change is evident in Figure 21 from 1 through to 20 applied volts. Figure 22 shows miniscule changes resulting from small changes in applied frequencies of RF field at 5 V ± 0.001 V. Figure 23 shows major changes resulting from significantly different frequencies in the applied RF at 5 V ± 0.001 V. All chart axes are simplified for readability but use the same precision as the above paragraph demonstrates.

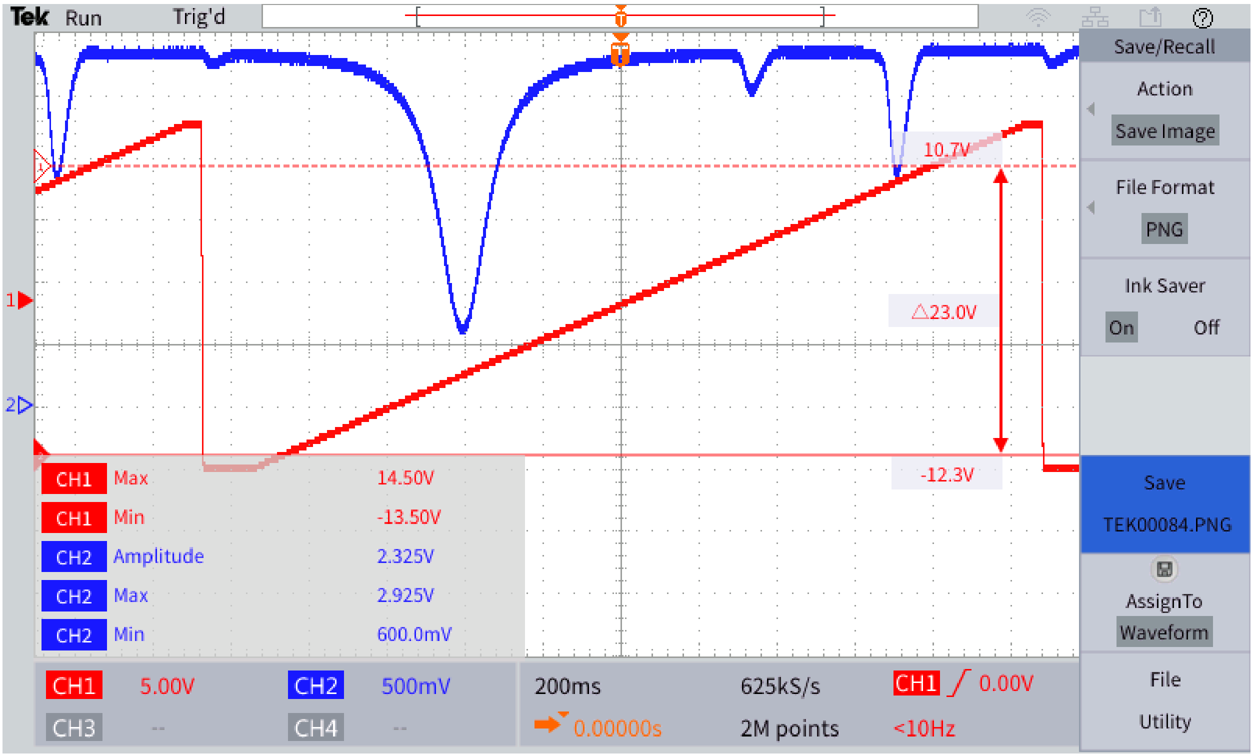

Figure 18: Most Prominent Resonance Levels

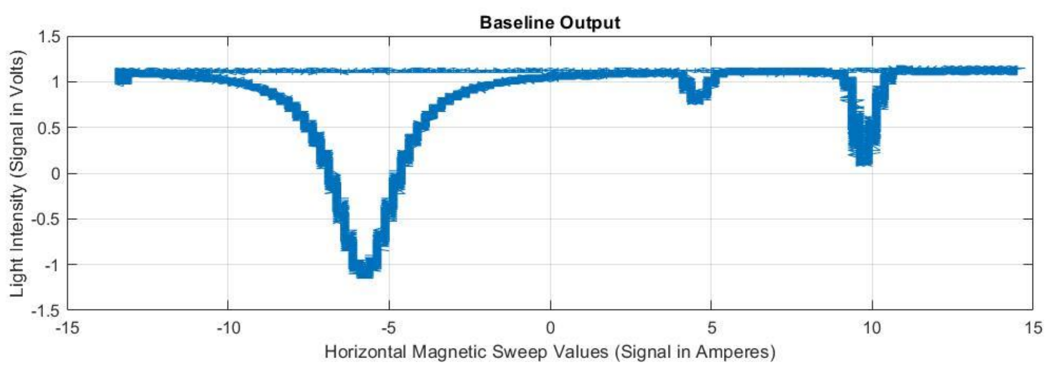

Figure 19: CSV File 10 Output Recording

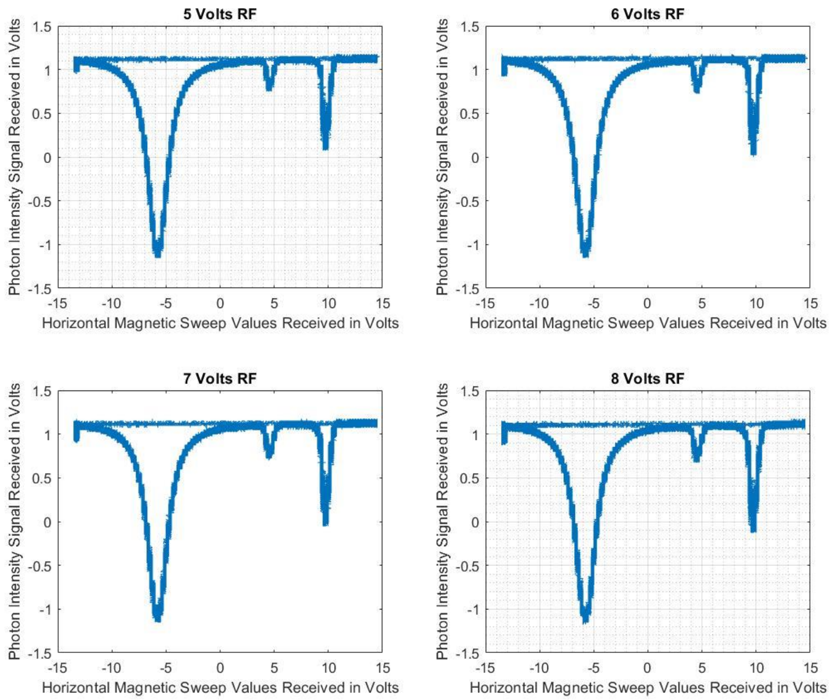

Figure 20: Slight Voltage Change Results in Varying Resonant Responses

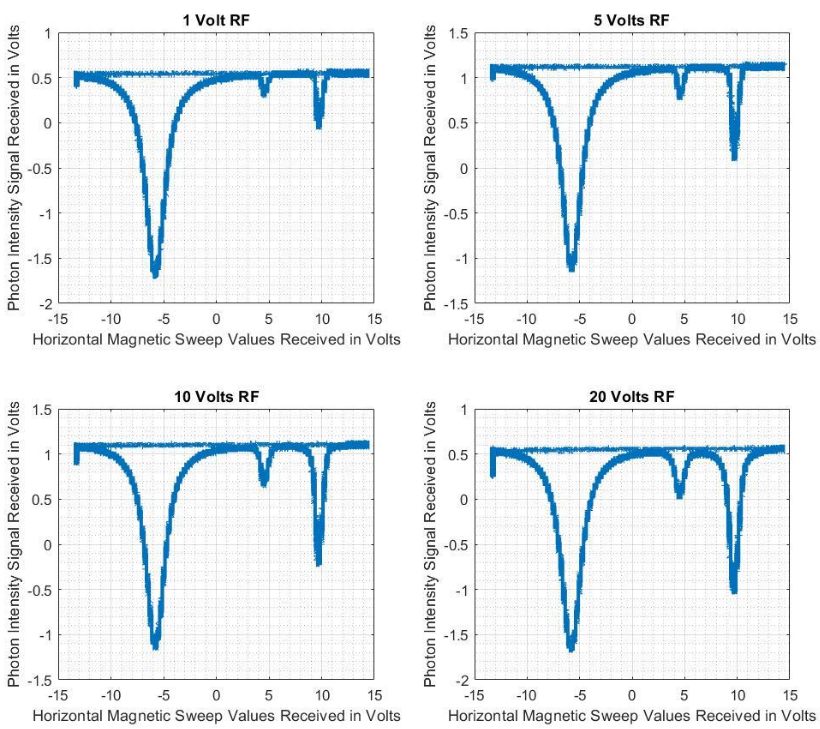

Figure 21: Obvious Changes as Applied RF Voltage Varied

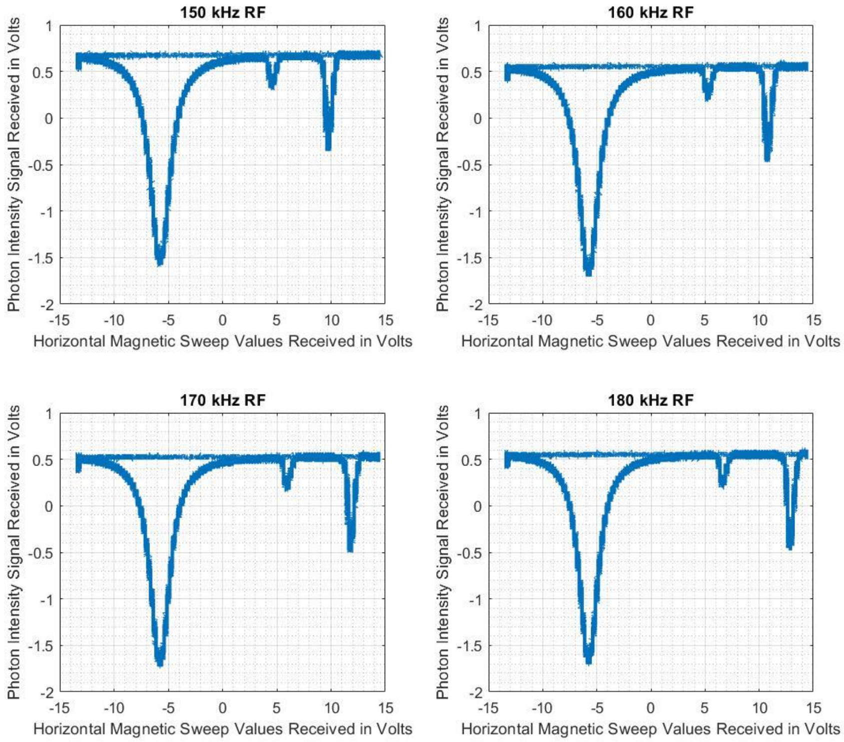

Figure 22: Miniscule Differences Evident During Applied RF Step Changes in 10 kHz Increments

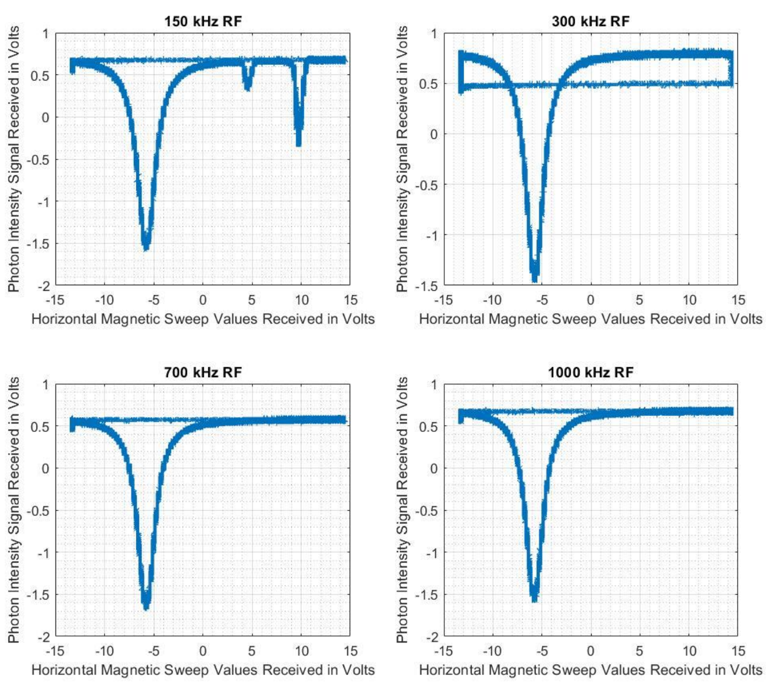

Figure 23: Major Resonant Frequency Changes with Differing RF Frequencies

Discussion

This lab was effectively a proof-of-concept to show analytical capabilities and rough changes that can occur with variable adjustments, along with some implications of those adjustments. However, due to the limited time available, only limited analyses were conducted on the collected data. A substantial amount of data was collected in this experiment. Using only the data collected from this 4-day experiment, I am estimating another 20 hours of analysis are possible with unused equations from the experiment handbook, evaluation of changing resonant frequency peaks, and finding new ways to match the data together to tell an interesting story about optically pumping rubidium atoms.

Finding the narrowest peak width was not particularly difficult. Therefore, the first experiment was comparatively easy and more like setup than experimentation. The second experiment (third chronologically if counting the botched data collection of the actual second experiment) was more time-consuming and generated substantial sums of data that were only barely analyzed for this paper. While collecting data for the second and third "actual" experimental collections, the sensitivity of the setup to temperature changes was recorded in Figure 24 during one of the times the thermocouple setup got disturbed. At one of the temperature extremes, optical pumping appeared to either disappear altogether or move outside the existing collecting parameters. This is shown by the flat line at the bottom of the readout samples.

Three or possibly four resonant Zeeman levels appear to have been found in the final experiment, as illustrated by the varying dip depths of Figures 18 through 23. The depth of the more minor Zeeman resonances changed according to applied voltage and frequency. The exact amount of the changes was not able to be determined from the short analysis of collected data. Much more analytical time is required to determine more information. Analysis was complicated by Excel's inability to properly process such large CSV files. As such, all graphical analysis was conducted in MATLAB and took longer than expected as I refamiliarized myself with the necessary coding.

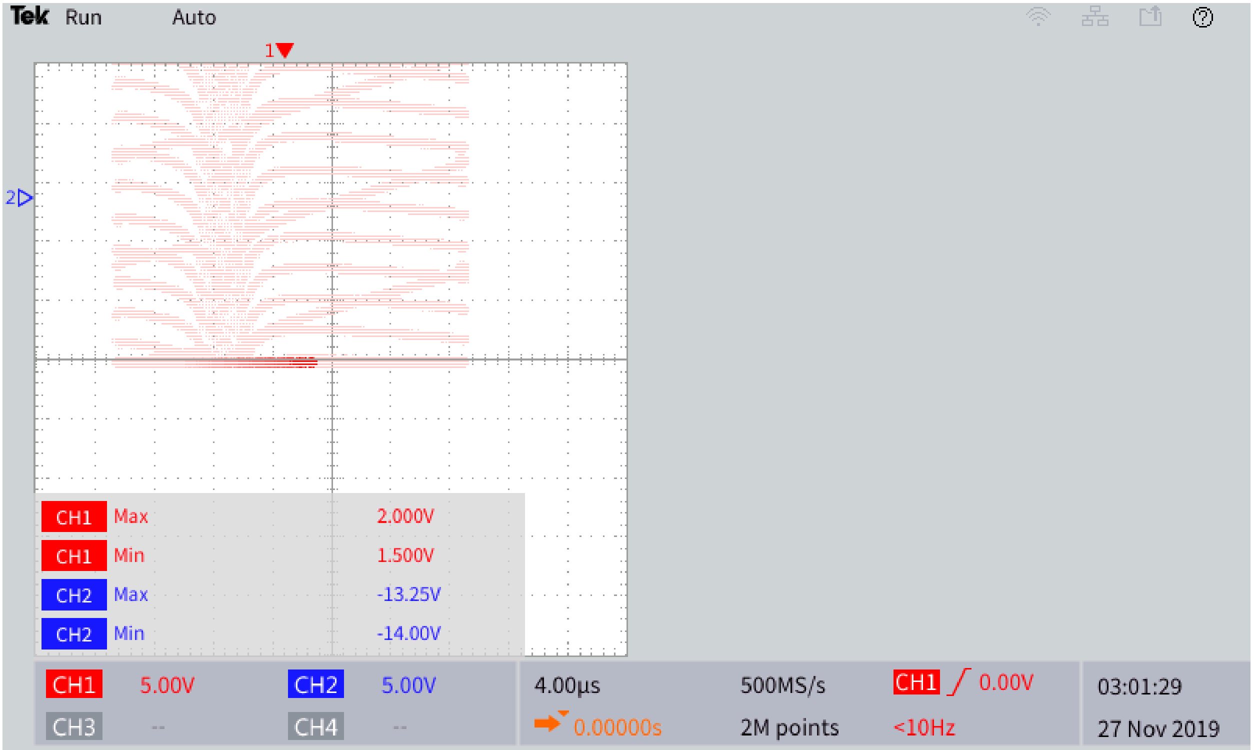

Figure 24: Temperature Fluctuations Move the Entire Graph

Conclusion

The peak width was easy to minimize with the vertical magnetic field was set to 2.42 dA ± 0.01 dA with the horizontal magnetic field sweeping from null to 0.985 V ± 0.001 V. Three Zeeman levels were readily found after applying an RF field of 150.00000 kHz $\pm 1 \cdot 10^{-5}$ kHz and 5 V ± 0.001 V along with a possible fourth level located at the start of each data collection cycle. Changes to both the voltage and frequency of the applied radio signal resulted in changes to the resulting graph. An ideal combination to maximize all Zeeman levels was not determined during this experiment. A calculation of Zeeman resonance frequencies was also not made, although the data should be present for future analysis.

References

1. Barbara Wolff-Reichert. A Conceptual Tour of TeachSpin's Optical Pumping, TeachSpin, February 2009.
2. David Vermillion. Optical Pumping Lab Manual, PHYS 475, December 2019

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[i] Barbara Wolff-Reichert. A Conceptual Tour of TeachSpin's Optical Pumping, TeachSpin, February 2009.
[ii] Barbara Wolff-Reichert. A Conceptual Tour of TeachSpin's Optical Pumping, TeachSpin, February 2009.