# Measuring the Hyperfine Splitting of Rb Excitation States with Saturated Absorption Spectroscopy

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#### Abstract

Knowing the excitation levels of atoms is valuable for experiments for identifying the atomic makeup of objects that release light from absorption. Techniques for measuring the excitation levels of elements must fight Doppler broadening to achieve low uncertainty. The purpose of this experiment is to test the technique of saturated absorption spectroscopy in the context of finding hyperfine energy splitting values in Hydrogen-like atoms. The results showed that with our methodology, we could not find all the hyperfine splitting states. The splitting energies we found had an average uncertainty-to-value ratio of 9%. We identified multiple ways to improve the experiment and expect that with those improvements there will be a great increase in how many states can be found and at higher precision. With some modification to the methodology presented in this paper saturated absorption spectroscopy can be a very good tool for finding the excitation energies of elements that are very close together.

### I. INTRODUCTION

In the early 1900's it was discovered that photons can be treated as particle-like clusters of quantized energy called photons [1]. This discovery was followed up by the development of quantum mechanics, which has shown that many phenomena that appear discrete at macro scales are actually discrete, but so close together that they appear continuous. One of the most visible examples of discrete effects predicted by quantum mechanics is discrete excitation energies for Hydrogen electrons, the Balmer Series. When an electron moves from one excited state to a lower energy state, a photon of a specific energy is produced, which is always the same frequency as given by the DeBroglie relation [2]. While Hydrogen has the most well-known excitation levels, all elements have different discrete excitation values. This fact is useful for spectroscopy where we want to know the atomic makeup of objects like stars [3].

In addition to the base energy level (generally labeled with the quantum number n), we see energy splitting between the quantum number for angular momentum l = 0 (labeled as S) and l = 1 (labeled as P). Depending on the total angular momentum J = S + L, where L is the orbital angular momentum and S is the intrinsic angular momentum, the P states will have different energies due to the electron coupling with the nucleus. This is called the fine structure. In the absence of any magnetic field, there is a degeneracy where all configurations of the quantum numbers that make up a state lead to the same energy levels [4]. However, the degeneracy is broken because of the magnetic interaction between the nucleus and the electron, causing more energy states that are separated by small amounts [2]. The result of all these effects on the different energy levels in Rubidium (Rb) is shown in figure 1. This is all easiest to do when working with Hydrogen-like atoms with one valence electron, such as Rb.



Figure 1. Reproduced from [4]. Displays the transition energies from Rb-85 and Rb-87 from the possible ground states to the excited states. Due to the effects of the nucleus, there is a hyperfine splitting in the ground state and excited state which require different amounts of energy to be excited to.

An electron can only be excited from one state to another if the difference in energy level is the exact energy of the photon that collides with it. Atoms in a gas are not stationary, they have velocities given by the Maxwell distribution. Two electrons moving at different velocities will see different apparent frequencies and by extension different energies of the incoming photons. The result is Doppler broadening, as shown in figure 2. In the case of Rb, the Doppler broadening causes the hyperfine energy splitting to be unresolvable without using Doppler-free spectroscopy section (described in II. Methods: B. Pump).

## II. METHODS

The experiment setup can be divided into three parts: the probe, the pump, and the wavemeter, as shown in figure 3. All three sections of the setup require the same laser, but the laser needs to have a variable frequency



Figure 2. Reproduced from [4]. Due to the movement of Rb particles in the cell, there will be a Doppler broadening effect. The left plot shows a Doppler broadened peak. The right plot shows that when a pump laser is sent into the Rb cell in the other direction it will excite Rb atoms that are not moving in the direction of the laser. The result is that there will be a tighter peak inside the Doppler broadened peak where the two lasers have to split the atoms that could be excited.



Figure 3. Reproduced from [4]. Set up for the experiment. A laser is split into three beams. Two beams are directed to enter a cell of gaseous Rb in opposite directions. These beams overlap as much as possible inside the cell, and one of them (labeled the probe) is then measured by a photodetector. The third beam is sent into an interferometer and the resulting fringe pattern is measured by another photodetector. Both photodetectors are connected to the same oscilloscope.

that can be controlled to change as a function of time.

## A. Probe

Direct a laser that has a variable frequency into a cell of a gaseous mixture of Rb 85 and Rb 87. The probe beam should pass through the Rb cell and be directed to a photodetector connected to an oscilloscope. As the laser's frequency scans over a range of interest, the oscilloscope should show valleys corresponding to

the Doppler-broadened excitation states. Note that the laser must be scanning over the right frequency range to excite the Rb atoms. Choose a laser that generates photons with energies as given in figure 1.

#### B. Pump

The same laser is split so 10% remains as the probe, while the other 90% is directed around the Rb cell and back into the cell anti-parallel to the probe beam, without disturbing the pump's path to the photodetector. Where the oscilloscope showed valleys, there should now be disturbance inside those valleys where some of those disturbances look like the right plot in figure 2. These new thinner peaks are caused by the pump beam exiting a portion of the Rb atoms that are stationary, which means at that frequency we see a spike in intensity because a fraction of the atoms are being excited by the pump that used to be excited by the probe.

#### C. Wavemeter

Before the laser is split 90/10 for the pump and the probe, the beam should be split so 50% goes into the pump/probe and 50% is directed into an interferometer that splits the beam so one arm is much longer than the other, where the difference in arm length is  $\Delta L$ . The beams then recombine and into a different photodetector connected to the same oscilloscope. This should produce an oscillating pattern in addition to the result of the probe laser. This gives a tool to convert the results of the probe photodetector from time-space to frequency space.

## III. DATA

The data from the oscilloscope is shown in figure 4. All the data was collected into CSV files and displayed using Python and Matplotlib. The difference between the legs of the wavemeter was measured as  $\Delta L = 1.35 \pm 0.01$  m.

### IV. ANALYSIS

The intensity seen in the wavemeter plot oscillates because the laser in the interferometer constructively interferes whenever the laser's wavelength is an integer multiple of  $2\Delta L$ , or the intensity follows an equation similar to

$$I \approx 1 + \cos\left(2\pi \frac{2\Delta L}{\lambda}\right) = 1 + \cos\left(\frac{4\pi\Delta L\nu}{c}\right) \qquad (1)$$

This gives enough information to convert the time-space data into frequency-space by counting the number of peaks that have passed, and the relative distance to the next peak and multiplying by the conversation factor:

$$\frac{c}{2\Delta L} = 111 \pm 2 ~\mathrm{MHz/peak}$$

For example, in figure 4 the first hyperfine splitting peak is measured at about  $1.7 \pm 0.5$  peaks from the crest of the first orange peak, so it would be measured to have a relative frequency of  $300 \pm 200$  Mhz.

The uncertainty here will end up dominated by the peak counting, which can only get as accurate as the number of peaks, so the conversion to "peak space" will always come with a half-peak uncertainty. This is an incentive to increase  $\Delta L$  as much as possible. Since the uncertainty in peak counting dominates the uncertainty in where the peak is in time-space, we ignore this uncertainty. Figure 5 shows an example of the error for some of the hyperfine spitting states.

Six peaks can occur from any starting state. If the atom is in F = f to start, it can end up in F' =f - 1, f, f + 1 and it can be at the crossover peaks (f-1, f), (f, f+1), (f-1, f+1). Since we do not see six peaks, we need to use the existing values, as seen in figure 1 to determine which excited states we see. When figure 4 is translated into frequency space it is easy to see that the separation of the second clump and the last clump of peaks are the appropriate separation to be the Rb 85 peaks, where the middle peak is Rb  $S_{1/2}(F = 3)$  and the rightmost peak is Rb 85  $S_{1/2}(F=2)$ , which leaves the leftmost grouping as Rb 87  $S_{1/2}(F=2)$ . Placing lines with the expected separation for all six possible peaks lets us match the possible solutions to the peaks we see (figure 6). The location of the possible peaks that best match the seen peaks gives us the list of peaks we are seeing.

Ground State
Leftmost
Middle
Rightmost

Rb-87 
$$S_{1/2}$$
 (F = 2)
(F' = 1)
(F' = 1, 2)
(F' = 1, 3)

Rb-85  $S_{1/2}$  (F = 3)
(F' = 2, 4)
(F' = 3, 4)
(F' = 4)

Rb-85  $S_{1/2}$  (F = 2)
(F' = 2)
N/A
(F' = 2, 3)

Table I. Results of the experiment based on the separation of the peaks we see and the data from [5] and [6]. This is based on the data in figure 4 and analysis demonstrated in figure 6.

#### V. RESULTS

Using the techniques in section IV we compiled the list of excited states that the data in figure 4 correspond to (table I). Table I shows the most likely results but there were multiple ways to place the possible peaks over the measured ones to produce similar results, and with errors as large as shown in figure 5 there are many configurations that are possible given the uncertainty.

To determine which of the possible configurations is the correct match we look at the probabilities of transitions happening using the coefficients described in [5] and [6].

#### VI. DISCUSSION

While we were able to definitively see that the addition of a pump beam allowed us to see hyperfine energy splitting, we were not able to see the full range of expected peaks and were required to use preexisting measurements to determine which peaks we saw. Additionally, the uncertainty in our measurements is large. Even with the coefficients defining the probability of a transition, we were not able to determine which Rb-87 transitions we found. However, our results did match very well with published results, where even the relative sizes of the peaks were very similar for Rb-85 [7].

There are two clear ways to improve on this experiment: a longer  $\Delta L$  and higher resolution data. The uncertainty from the peak counting was the dominant uncertainty in the measurement, so reducing that will increase confidence by a lot. Increasing the resolution of the data will be helpful because we want to make sure peaks that are small but close together can still be seen, even if they are not resolvable. We then want to record data with and without the pump laser so we can subtract them. This might reveal peaks that are currently hidden from us due to the shape of the Doppler broadened peaks.

## VII. CONCLUSION

This report shows that it is possible to find excitation energies of Rb using saturated absorption spectroscopy. While Rb was the choice target for this experiment, the technique is not dependent on Rb and can be used in



Figure 4. Plotted data recorded from the oscilloscope. The orange is a fine pattern resulting from an interferometer and is used as a measuring tool to convert the time stamps into frequency values. The blue is the intensity of the probe laser after passing though the Rb cell. The time value is representative of some frequency changing as a function of time.



Figure 5. Shows the uncertainty in the frequency (orange) plotted over the data of the transitions from the  $5S_{1/2}(F = 3)$  state from figure 4 in frequency space.

general to resolve individual peaks that would have been hidden due to Doppler broadening. While our results had large uncertainty, it was dominated by the distance between peaks in the wavemeter, and increasing  $\Delta L$  will significantly help.

Precise measurements of excitation levels are valuable for spectroscopy. Seeing photons coming off something that are separated by the same relative amounts (or multiplied by a factor) as the excitation levels of an element's excitation energies astronomers can determine that there is some of that element in the region they are looking. Exciting certain elements is also a way to produce certain colors of light. We also need to be able to find the hyperfine splitting energies to compare against predictive models to test how accurate they are.



Figure 6. The green dotted lines are the correct spacings for the energies of Rb-85. They have been shifted into place based on the best match to where the peaks are and the coefficients from [5].

This method did not produce all of the hyperfine splitting energies, but with a better wave meter and a higher resolution photodetector, this method is a promising way to find the hyperfine splitting energies of Hydrogenlike atoms, and possibly of other elements. This technique can benefit from further experimentation with the methodology corrections we discussed.

## VIII. ACKNOWLEDGEMENTS

This experiment based on the lab manual [4]. Chat-GPT was used to create the citations used in this paper [8].

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