Laser Spectroscopy of Rubidium

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In this experiment, we used laser spectroscopy to look at the hyperfine splitting of Rubidium (Rb) as well as calculated the temperature of the gas with the use of Doppler broadening theory. We found a room temperature of 323 K ± 50 K. We also found the energy difference between F'=1 and F'=2 to be 161 MHz ± 25 MHz and F'=2 to F'=3 to be 264 MHz ± 25MHz. We were unable to resolve the hyperfine structure for Rb 85.

I. INTRODUCTION

Atomic spectra are vastly useful for not only testing quantum theory (the goal of this experiment), but especially for the field of astronomy as well. Spectra are unique to each atom and in this way astronomers have used atomic spectroscopy to deduce compositions of atmospheres of other planets, and compositions of the stars, including our sun. Within the realm of quantum mechanics, major theories are able to be tested through high resolution atomic spectroscopy. One of said theories that we will test is the hyperfine structure of both isotopes of Rb atoms.

This paper begins with a bit of the theory which includes, but not limited to: hyperfine splitting of both the ground state and first excited states of Rb, crossover resonance, saturated absorption and Doppler broadening. Section III covers the experimental set-up, with explanations for each piece of equipment used. Then section IV will discuss results and, sadly, the paper concludes with an analysis of uncertainty section V.

II. THEORY

A. Into the Realm of the Hyperfine

Most things attempt to stay in a sate which draws the smallest amount of energy from itself and its surroundings, atoms included. Although, the electrons of atoms can be placed in an excited state with the help of a photon which has a very specific frequency corresponding to the "jump" of energy state the electron takes. This specific frequency is simply the difference of energies between the two energy states. This basis can be used to make sense of FIG. 1 or vice-versa. However, quantum mechanics allows a deeper understanding of FIG. 1 as well a basis for hyperfine splitting.

Some valuable quantities regarding atoms are the electron's orbital angular momentum, L, (0 for ground state and 1 for the first excited state) its spin angular momen-
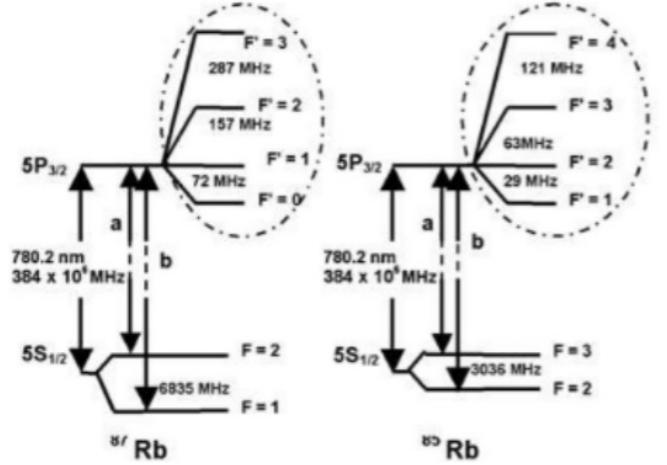
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FIG. 1. Possible hyperfine transitions for Rb 85 and Rb 87.

tum, S, and the combination of those, yields the electron's total angular momentum, J. To obtain an atom's total angular momentum the nuclear spin, I, is required. We know values of I for the ground states is 3/2 for Rb 87 and 5/2 for Rb 85. We can now find the total angular momentum for the system, F, by the relation:

$$F = I \pm J. \tag{1}$$

Upon inspection, one can see how values of F are obtained if one knows that the in the ground state for Rb J is ± 1/2. Looking at FIG. 1 again we see the first excited state has a couple more F values to be obtained; this is because J is allowed to have another value, ± 3/2.

B. Doppler Broadening

In our experiment we had no means of cooling (or heating) our Rb atoms down close to absolute zero. We also know that there is a very large number of particles contained in a relatively larger volume so it is acceptable to implement Maxwell-Boltzmann statistics to describe our sample of Rb. We can write our distribution (in one direction) of the velocities as

$$D(v)dv = (\frac{m}{2\pi kT})^{3/2} e^{-mv^2/2kT} dv, \tag{2}$$

where v is the velocity of the particle, m is the particle's mass, k is the Boltzmann constant $(1.38 * 10^{-23})$ J/K and T is the temperature of our sample. This distribution yields a variety of speeds our Rb atoms can have which affects the frequencies the atoms interact with the photons due to the Doppler effect. The Doppler effect is expressed as

$$f = f_0(1 + v/c), \tag{3}$$

where f_0 is the frequency of the photon in a stationary frame of reference, v is the particle's velocity, c is the speed of light and f is the frequency observed by the particle. What this means for us is atoms which would not make a transition due to an incorrect resonance could now able to do so if the difference is corrected for by the Doppler shift. This gives a much wider peak for our absorption spectra. With some quick algebra we can change Eq. (3) to yield

$$\frac{\Delta f}{f} = \frac{v}{c}. \tag{4}$$

We can use this nice little relation and make a substitution into Eq. (2) to get

$$D(f)df = (\frac{m}{2\pi kT})^{3/2}e^{-mc^2(\Delta f)^2/2kTf_0^2}dv. \tag{5}$$

Now we need a consistent way to measure values that vary from the peak distribution, let us say all particles that lie within the full width that occurs at half the peak, or Full-Width Half-Maximum (FWHM). To obtain half the maximum we set our exponential equal to ln(2) then solve for Δf which gives us the "width" of our peak, of course we must to multiply by 2 to obtain the full width. We can now analytically solve for the FWHM by

$$\Delta f = \sqrt{\frac{8ln(2)kTf_o^2}{mc^2}}, \tag{6}$$

and we can solve for temperature and obtain:

$$T = \frac{mc^2}{8ln(2)k}(\Delta f/f_0)^2. \tag{7}$$

C. Saturated Absorption

In an effort to reduce the ill effects of Doppler broadening we implement saturated absorption. This technique splits the laser of the resonant frequency so that it hits the sample at opposite sides with one beam being much stronger than the other. This causes particles that are Doppler shifted with the axis of the lasers to either interact with a "pump" (strong) beam or a "probe" (weak) beam, but not both. However, when the beam is at the

resonant frequency the pump beam "pumps' the sample into a higher energy state causing the probe beam to not be able to interact with that proportion of the sample resulting in a single "dip" in the peak.

D. Crossover Resonances

When a resonance occurs we see a single dip in our absorption peak. Unfortunately, there a multiple resonances for each hyperfine transition. So, the pump beam for one resonance may coincide with the probe beam of another resonance creating what is known as a crossover resonance.[12]
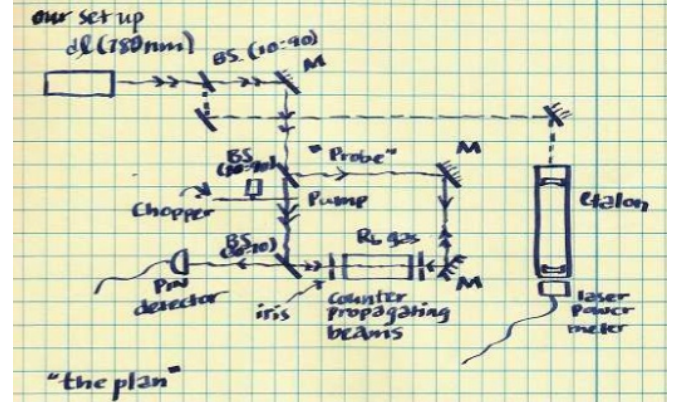
III. APPARATUS

A. Apparatus

FIG. 2. Schematic of the experimental apparatus used for saturated absorption.

The diagram in FIG. (2) shows the relevant block diagram and general set-up for the experiment. First we have a 780.2 nm tunable laser diode to sweep through the resonant frequency range from the ground state to the first excited state of Rb. The laser first gets split so one path leads to the etalon. The etalon is there because we do not know the rate of the frequency sweep by the laser. It gives us a "frequency ruler" of sorts because it produces a signal which occurs periodically based on frequency. The beam that does not pass through the etalon continues and becomes split again into our pump and probe beams. The probe beam passes through the sample and enters a PIN detector which then produces a signal to be read off of an oscilloscope. We also use a device known as a lock-in amplifier. This device allows us to eliminate a huge amount of noise in combination with a chopper. The copper cuts the beam into a certain frequency and the lock in compares the frequency of reference beam to the signal beam. If they are out of phase, typically noise, then there is no output. This gives us a

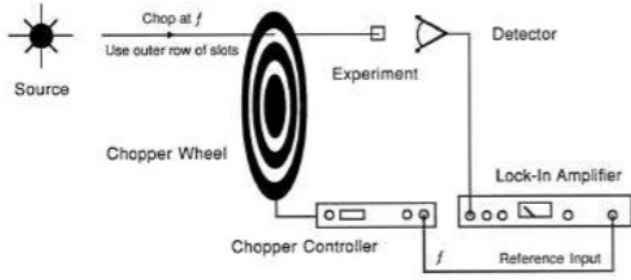much greater resolution. A diagram of the chopper with the lock in is seen in FIG. 3.[3]

FIG. 3. Diagram of a lock-in amplifier with chopper.

IV. RESULTS

A. Temperature of Rb gas

Our mathematical model for temperature is observed in Eq. 7 and using the FWHM of the peaks in FIG. 4 as well as data from the etalon allowed us to test theory with experiment. We obtained a temperature of 323K $\pm$ 50 K for the gas, the uncertainty of which contains the temperature of the room at the time, 296K.
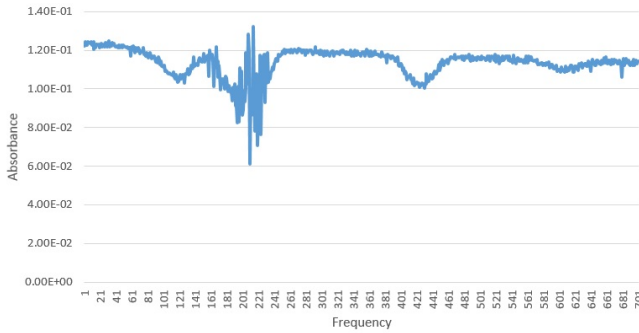

FIG. 4 Doppler broadened spectra for Rb 85 and Rb 87

B. Resolving the Hyperfine Structure

We were able to resolve much of the hyperfine structure for Rb 87 as seen in FIG. 5. Here we are able to make out the energy differences between F'=1 and F'=2 as well as F'=2 to F'=3; for these values we obtained differences of 161 MHz $\pm$ 25 MHz and 264 MHz $\pm$ 25MHz respectively. Theory (and FIG. 1) states these values should be 157 MHz and 287 MHz, so we can confirm theory for

F'=1 to F'=2 transition, but our F'=2 to F'=3 frequency falls short even when accounting for uncertainty. Unfortunately our technique and/or apparatus was unable to resolve the hyperfine structure for Rb 85; this can be seen in FIG. 6.
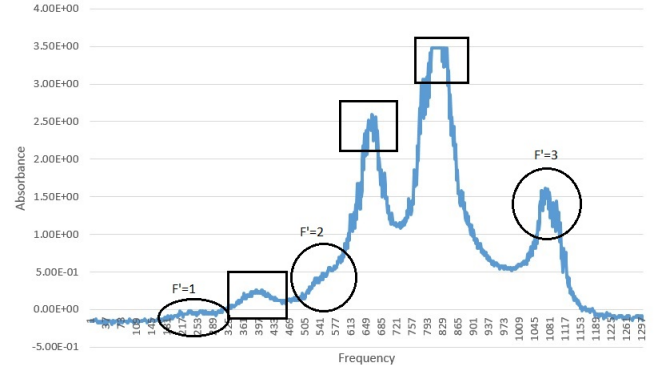

FIG. 5. The Doppler free Rb 87 spectra. The circles indicate a hyperfine energy state and squares are crossover frequencies.
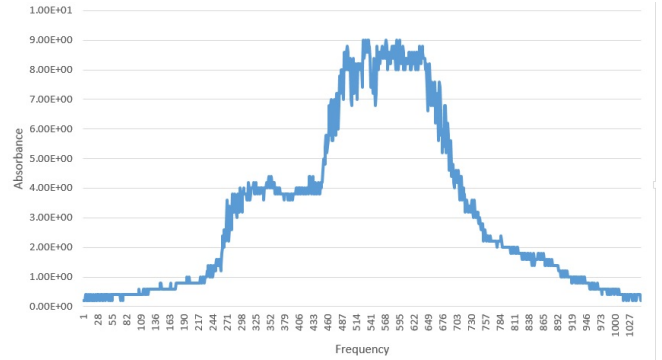

FIG. 6. The best resolution of Rb 85 from which we are unable to deduce energy levels.

V. CONCLUSION AND ERROR ANALYSIS

This experiment was a great way to inspect the hyperfine structure of atoms, even if we were limited to for one isotope. I really enjoyed testing statistical mechanics theory for this system rather than a strict quantum perspective. Almost all uncertainty and error came from either miss reading where peaks occur in the etalon data, making our "ruler" inconsistent, or just plain wrong, and difficulties in reading the peaks in the absorption spectra.

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