

# Absorption spectroscopy of rubidium gas

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High resolution laser spectroscopy is used to probe the energy level make up in a rubidium gas. Doppler broadened absorption probes the hyperfine structure of the ground state in rubidium 85 and 87. We find that the energy gap for the doublet  $S_{1/2}$  states in rubidium 85 is  $3030 \pm 51 MHz$  while in rubidium 87 the gap is  $6700 \pm 112 MHz$ . We determine the temperature of the gas to  $310 \pm 33 K$ . The temperature of the gas is determined to be  $310 \pm 23 K$ . Saturation absorption spectroscopy of rubidium 87 gives energy gaps of  $290 \pm 31 MHz$  for the  $F = 3 \rightarrow 2$  transition and  $120 \pm 42 MHz$  for the  $F = 2 \rightarrow 1$  transition.

## I. INTRODUCTION

Absorption spectroscopy allows us to determine the energy levels in atoms. The theory of atomic absorption was first conceived of by Albert Einstein in his paper detailing the photoelectric effect, one of his *Annus Mirabilis* papers<sup>1</sup>. The field of absorption spectroscopy has grown theoretically and experimentally so that we can use lasers to probe the atomic world. Arthur Schawlow won a Nobel Prize for his work in laser spectroscopy and explains many of the techniques we use in our experiments in his 1978 paper<sup>2</sup>.

In this paper we report our results of absorption spectroscopy of a rubidium gas. We use Doppler broadened absorption spectroscopy to determine the hyperfine splitting in the ground state of rubidium as well as the temperature of the gas. In addition, we use saturation absorption spectroscopy to probe the hyperfine structure in the first excited state of the gas.

In Section II, we present a theoretical grounding for the hyperfine splitting as well as some principles of laser spectroscopy. Section III describes the methods used. Section IV reports the results of the two experiments and Section V ends the paper with concluding remarks.

## II. THEORY

### A. Hyperfine Structure

High resolution laser spectroscopy takes advantage of the hyperfine splitting due to the spin-spin interaction between the nucleus and electron. It is typically defined that  $I$  is the spin of the nucleus and  $J$  is the spin of the electron. The total spin of the atom,  $F$ , is defined to be the sum of  $I$  with  $J$ . This then means that the perturbing Hamiltonian will have the following form<sup>3</sup>:

$$H_{hf} = A(\hat{I} \cdot \hat{J}), \quad (1)$$

where  $A$  is a constant termed the Fermi contact parameter whose value can be determined through a first principles electrodynamics calculation<sup>4</sup>. This Hamiltonian will split the ground state of rubidium into two states with an energy difference of  $2A\hbar^2$ . Given the eigenbasis  $|FM_F\rangle$  one can work out the calculation to find that

the hyperfine Hamiltonian will lift the upper state to a value of  $\frac{3}{4}A\hbar^2$  and drop the lower state to a value of  $-\frac{5}{4}A\hbar^2$ . The hyperfine Hamiltonian will split the degenerate states into  $2J + 1$  separate states each with their own corresponding energy. This means that the excited states will also experience a hyperfine splitting, albeit with a much smaller energy gap between states. Figure 1 shows a partial energy level diagram of the ground state and first excited state in rubidium.

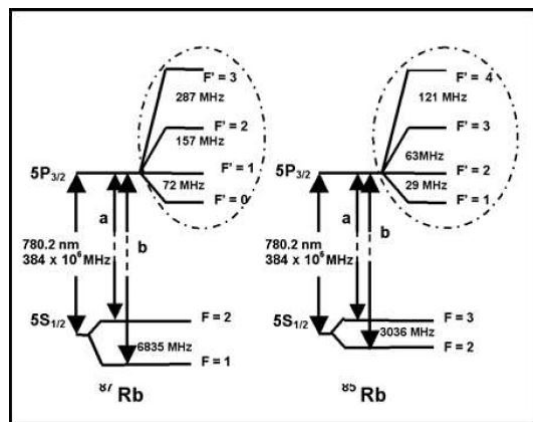


FIG. 1. Partial energy level diagram of rubidium including hyperfine splitting. Energy gaps are labelled in frequency units.

### B. Doppler Broadening

In any gas, there will be a distribution of velocities among the constituent gas particles that is Maxwellian in nature<sup>5</sup>. If we hit our atomic gas with light of a specific frequency,  $\nu_1$  the atoms moving with some component velocity,  $v_z$ , along the laser path will only experience absorption phenomena if the frequency of light,  $\nu$ , is<sup>5</sup>:

$$\nu = \nu_1 \left(1 + \frac{v_z}{c}\right), \quad (2)$$

which is just well-known doppler shift for  $v_z \ll c$ . This means that laser with frequency equal to  $\nu_1$  will interact only with that set of atoms moving at velocity  $v_z$ . As we are attempting to obtain an absorption spectrum, the

Doppler effect will tend to broaden the absorption band. Because the Doppler width is much larger than the energy gaps in the excited states, Doppler broadening prevents us from exploring the hyperfine structure in the excited states but does allow us to learn about the splitting in the ground state. By using Maxwell-Boltzmann statistics we can define the full width half max to be<sup>5</sup>:

$$\Delta\nu_{\frac{1}{2}} = \sqrt{8k_B \log(2)} \frac{\nu_1}{c} \sqrt{\frac{T}{m}}. \quad (3)$$

Knowledge of all pertinent values in equation 3 allows us to find the temperature of the gas which should be nearly the temperature of the gas' surroundings.

### C. Saturation absorption spectroscopy

In our experiment we use saturation absorption spectroscopy which is a technique to observe the hyperfine structure of the excited state in a gas. This technique uses counterpropagating laser beams that interact with groups of atoms with equal magnitude but opposite direction velocities. As we tune the laser through a range of frequencies we can induce transitions among the different excited states. It is possible that due to the interaction with different groups of atoms that crossover peaks may occur. These crossover frequencies will occur at<sup>6</sup>:

$$\frac{\nu_1 + \nu_2}{2}, \quad (4)$$

where  $\nu_1$  and  $\nu_2$  are the corresponding transition frequencies of two different states. These peaks are quite noticeable as seen in section IV.

## III. METHODS

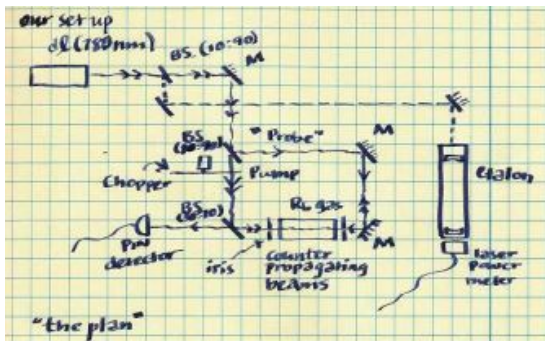


FIG. 2. A block diagram of the laser spectroscopy set up.

Figure 2 is a schematic detailing the laser spectroscopy set up. We do both saturation absorption as well as 'simple' absorption experiments with a rubidium gas. The laser used is a tunable diode laser with wavelength 780.1 nm. This laser is sent through a beam splitter and one

beam is sent to an etalon and the second is destined to hit the rubidium gas. An etalon is a device that can be used as an optical ruler. As we are tuning our laser the etalon will pick up changes of 300MHz. This data is sent to an oscilloscope and we can use this data to convert from samples to megahertz. This is how we determine frequency gaps between energy levels.

The beam that is to be sent to the rubidium gas is again split into 'pump' and 'probe' beams. The probe beam is sent to the right side of a rubidium gas cell while the pump beam is sent to the left side of the cell. Since the beams are both of the same frequency this allows for the beams to act with groups of atoms moving with velocities of the same magnitude but opposite direction. As we tune the laser the groups of atoms will change until both beams act upon the same group of atoms and we obtain the transition we expected. A chopper is used to send a frequency signal to a lock-in amplifier that improves the signal to noise ratio. The data is then collected by a PIN diode.

Completing the experiment the above way is used for saturation absorption spectroscopy, but we can also do basic absorption experiments. To do these experiments we turn the chopper off and block the pump beam. All other components remain the same.

## IV. RESULTS AND DISCUSSION

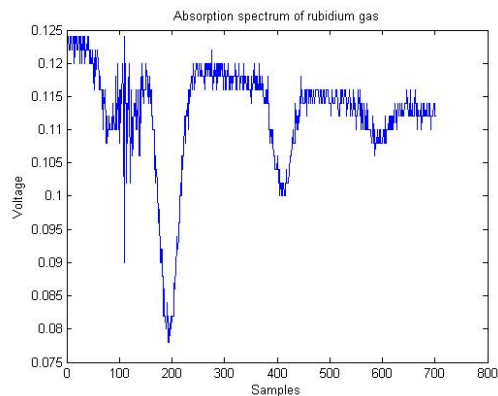


FIG. 3. Plot of the rubidium absorption spectrum. The left most and right most dips correspond to rubidium 87 while the center dips correspond to rubidium 85. Due to the doppler broadening the excited state data cannot be seen on this plot.

Using only the probe beam of our laser we were able to determine the hyperfine splitting of the ground state of both rubidium isotopes. The absorption dips can be seen in figure 3. For rubidium 85 the hyperfine splitting is  $3030 \pm 51 MHz$  while in rubidium 87 the splitting is  $6700 \pm 112 MHz$ . Previous experiments<sup>7</sup> show that the value for rubidium 85 is  $3036 MHz$  which is within 0.2% of our value. For rubidium 85 the same previous experiment quotes a hyperfine splitting value of  $6834.7 MHz$

which is within 2% of our value. The value, including the error, of rubidium 85 includes the accepted value while the value for rubidium 87 does not.

As stated in section III, we use an etalon as a sort of ruler. This allows us to determine the frequency change per sample. Since the etalon peaks occur over a range of samples this leads to difficulty in determining the number of samples between etalon peaks. We found that the number of samples between successive peaks is  $23 \pm 1 \text{ samples}$  leading to a value of  $13.0 \pm 0.5 \frac{\text{MHz}}{\text{sample}}$  which explains the error in hyperfine structure values.

Using the fact that the absorption spectrum is Doppler broadened, we can use equation 3, which relates the full width half max (FWHM) to the temperature, to determine the temperature of the gas. With a FWHM value of  $585.6 \pm .2 \text{ MHz}$  and a  $\nu_1$  value of  $3.84 * 10^8$  from the laser frequency we determine the temperature to be  $310 \pm 23 \text{ K}$  which just barely includes the value for room temperature of  $293 \text{ K}$ . Similar to the energy gaps, the error here can also be attributed to the variability in the etalon spacing. There is also some variability in determining both the peak of the absorption spectrum as well as the FWHM value. Figure 4 shows the saturation absorption

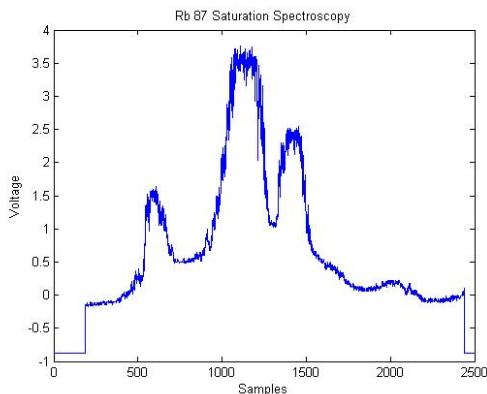


FIG. 4. Saturation absorption spectroscopy of rubidium 87. Three of the peaks come from the actual transitions while the other three come from the crossover transitions.

spectrum of rubidium 87. From this data we find that the energy gaps between the energy levels are  $290 \pm 31 \text{ MHz}$  for the  $F = 3 \rightarrow 2$  and  $120 \pm 42 \text{ MHz}$  for the  $F = 2 \rightarrow 1$  transition. These values are both within 30% of the accepted values<sup>5</sup>. Both values with the error also include the true values. This error again could come from the

etalon but in addition to rubidium the gaps between the peaks are fairly close together that an increase in the number of samples would give more accurate values. We also can deduce that these transitions came from the  $F = 2$  ground state based on the selection rule  $\Delta F = 0, \pm 1$ . Figure 5 shows the saturation absorption spectrum for rubidium 85. With the resolving power of our set up we were unable to resolve the pertinent features. This results from the much smaller splitting of energy levels<sup>5</sup> in rubidium 85 than in rubidium 87.

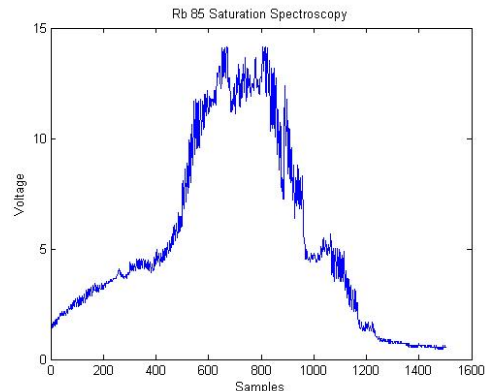


FIG. 5. Attempt at saturation absorption spectroscopy in rubidium 85. The features could not be resolved with our set up.

## V. CONCLUSIONS

We have presented results for absorption experiments in rubidium 85 and 87. Doppler broadened absorption allowed us to report the temperature of the rubidium gas as well as the ground state hyperfine splitting. Saturation absorption allowed us to determine the hyperfine structure of the first excited state in rubidium 87 while the resolving power prevented these results in rubidium 85.

<sup>1</sup>A. Einstein, *Annalen der Physik*, **14**, 1 (1905).

<sup>2</sup>A. Schawlow, *Science*, **202**, 13 (1978).

<sup>3</sup>D.J. Griffiths. *Introduction to Quantum Mechanics*. (Pearson Education Inc., Upper Saddle River, 2005).

<sup>4</sup>J.D. Jackson *Classical Electrodynamics 3rd ed.* (Wiley, Hoboken, 1998) p. 184.

<sup>5</sup>D.W. Preston, *Am. J. Phys.* **64**, 11 (1996).

<sup>6</sup>K.B. MacAdam, A. Steinbach and C. Weinman, *Am. J. Phys.* **60**, 12 (1992).

<sup>7</sup>G.M. Rao, M.N. Reddy and E. Hecht, *Am. J. Phys.* **66**, 8 (1998).