An Exploration of Hyperfine Structure of Rubidium Within the $5P_{3/2}$ Excited-State Using Saturated Absorption Spectroscopy

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Introduction

In direct absorption optical spectroscopy, the Doppler broadening of spectral lines often prevents us from studying the hyperfine structure of an atom [1]. With Saturated Absorption Spectroscopy (SAS), this effect can be overcome and can be used to precisely study the finest energy splittings within an atom [2]. In the SAS setup, two low-power beams produced by an external-cavity diode laser is sent through a vapor cell containing rubidium while another strong (high-power) beam from the same laser crosses one of the two beams in the opposite direction through the vapor cell. With atoms absorbing more photons from this strong beam, the low-power beam then shows less absorption while the laser is scanning through the transition. By directing the two low-power beams at a differential photodiode, an atomic spectrum corresponding to the hyperfine energy levels can be obtained. Using this technique, here, we measured the hyperfine energy splitting ratios of the first excited state of rubidium using the $5S_{1/2} \rightarrow 5P_{3/2}$ transition at 780.24 nm.

Energy Level Structure of Rb

Rubidium has two major isotopes: 72% of ^{87}Rb and 28% of ^{85}Rb. The split between 5S and 5P orbitals is part of the fine structure level and can be identified by L-S coupling (electron orbital- and spin-interaction) scheme with notation $^{2S+1}L_J$.

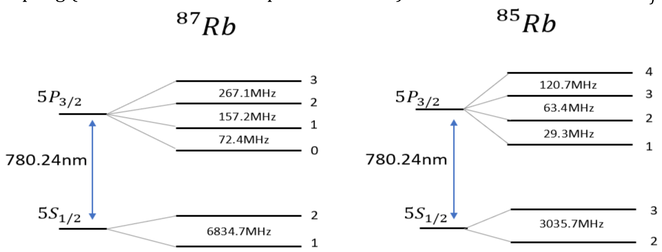


Figure 1: Hyperfine structure of rubidium for two isotopes

Due to the electron spin and nuclear spin interaction, the fine structure levels are split into hyperfine energy levels as shown in the figure 1. Hyperfine energy levels are characterized by the total angular momentum quantum number F which is the sum of electron angular momentum J (L+S) and the nuclear spin angular momentum I. F has allowed values between $|J - I|$ and $J + I$, in integer steps [3].

Saturated Absorption

When the strong beam crosses one of the two low-power beams, the direct absorption spectra associated with two beams are different. One is a direct absorption spectrum (yellow) and the other shows the direct absorption with saturated absorption features (Blue).

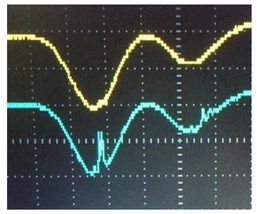


Figure 2: Direct absorption spectrum (yellow) and direct absorption spectrum with hole burning effect (blue).

When ground state atoms are in resonance with the strong beam they absorb more photons from that beam and as a result, the direct absorption signal from the crossed low-power beam shows less absorption at those frequencies (Blue). This is called the "hole burning effect" in the direct absorption dip. The hole burning can occur at hyperfine transition frequencies as well as at exactly in the middle of those frequencies due to the Doppler effect-caused transitions (cross-over resonance).

Experiment

On an optic table, the laser beam from the ECDL first passes through a variable attenuator and is then reflected towards the beam splitter. The beam splitter directs two low-power beams (Beams A and B) through the rubidium vapor cell. The strong beam (Beam C), which passes through the beam splitter, is reflected using several mirrors to cross one of the low-power beams, Beam B, in the opposition direction. The two low-power beams, after going through the vapor cell, are directed towards a differential photodiode and cross converging lenses to have a focus on the photodiode.

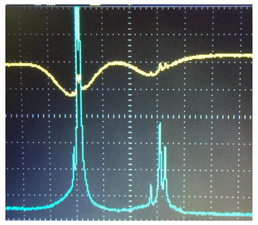


Figure 3: The raw data, absorption spectra observed on an oscilloscope. Direct absorption spectrum with burning hole effect (yellow). Saturated absorption spectrum (blue) is the difference signal between direct absorption and direct absorption with burning hole

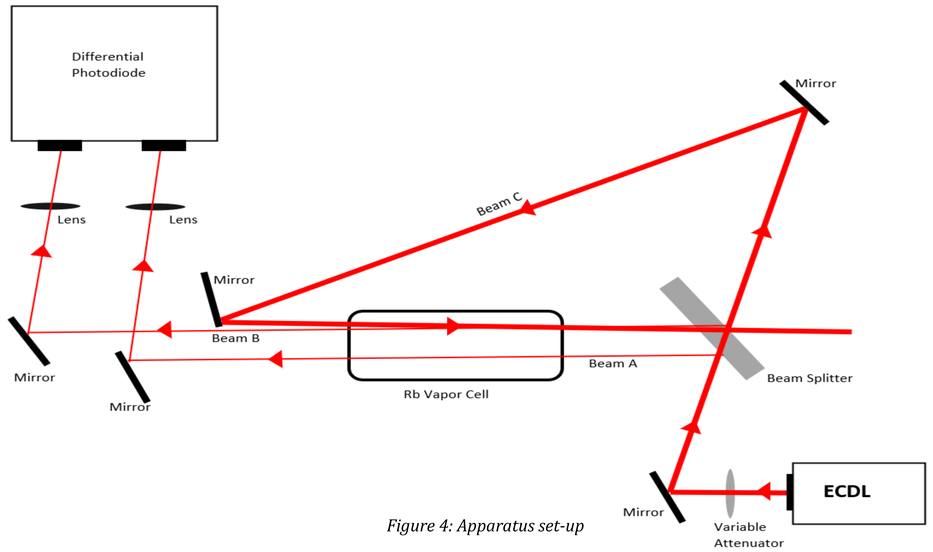


Figure 4: Apparatus set-up

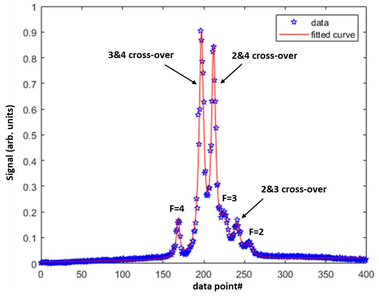
Data Analysis

Twenty sets of saturated absorption for ^{85}Rb and ^{87}Rb were collected using LabVIEW and analyzed using MATLAB.

The raw data were fitted to Lorentzian line shapes (equation on the right) and a linear function to adjust the base line.

$$I(x) = I_o \frac{\Gamma^2}{(x - x_o)^2 + \Gamma^2}$$

I_o is height of peaks, x_o is the position of peak on the x-axis and Γ is the half width at half maximum



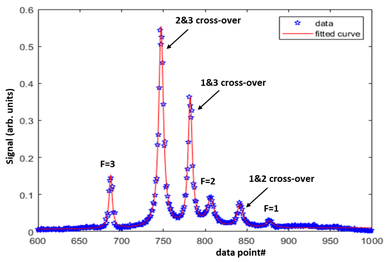


Figure 5,6: The fitted saturated absorption spectrum for ^{85}Rb (*left*) and ^{87}Rb (*right*).

Notice that the three of the peaks for each isotope represent hyperfine transitions and the other three are crossover peaks.

Figure 7 shows the histogram of hyperfine splitting ratio values determined from measured splittings ΔF_{23} and ΔF_{34} by analyzing ^{85}Rb spectra.

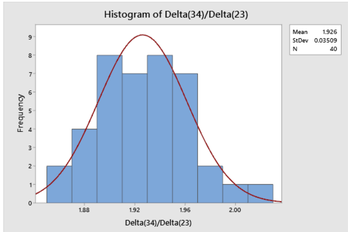


Figure 7: Histogram of the ratio for ^{85}Rb.

Results

The hyperfine splitting ratio $\frac{\Delta F_{34}}{\Delta F_{23}}$ in ^{85}Rb was found to be 1.93±0.04 with a percent difference of 1.6% with the theoretical value. Similarly, the ratio $\frac{\Delta F_{23}}{\Delta F_{12}}$ in ^{87}Rb was found to be of 1.71±0.02 with a percent difference of 0.6% with the theoretical value. All error bars above represent only the statistical error.

Conclusion

Through saturated absorption spectroscopy, the hyperfine splitting energy levels from $5S_{1/2} \rightarrow 5P_{3/2}$ transition in rubidium were observed carefully. The use of both hyperfine level peaks and crossover peaks increased the statistical precision of the results.

Future Work

In a future study, we will capture the saturated absorption spectrum along with the Fabry-Perot cavity spectra. This will allow us to establish a linearized frequency axis and hence determine the hyperfine energy splittings explicitly.

Acknowledgement

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