

# Saturated Laser Absorption Spectroscopy: Parameterizing the Hyperfine Transitions of Natural Rubidium

CANDIDATE [166952] FRANKIE HOMEWOOD<sup>1\*</sup>

<sup>1</sup> Dept. of Physics and Astronomy University of Sussex Falmer, Brighton BN1 9QH

Compiled April 4, 2019

Observing the hyperfine transitions probes the finest details of atomic structure which allows the investigation of physics on minute scales. Here we use a saturated laser absorption spectroscopy set up to identify, model and quantify the Lorentzian curve profiles of the hyperfine transitions in natural rubidium including crossover resonances as well as a calibration of the Fabry-Perot interferometer. This measurement is attained by method of gradual ramping of voltage input into the laser diode to vary the frequency over time, this produces a spectrograph in the order of  $10^6$  Hz which can be fitted to evaluate the different parameters of these curve profiles. The process resulted in four hyperfine fits with accurate measurements of relative frequencies, each fit had an average error in the order of  $\mu V$ . The measurements of the Doppler broadened spectrum produced an expected  $\Delta\nu_{FSR}$  which deviated from the given value by  $8.348 \pm 0.047\%$  indicating that there could be some deviation from the expected behaviour that is not accounted for in the measurement.

## Preface

All of the work present in this paper is a product of my own labour, the work within the laboratory was a product of the joint labour between laboratory partner Nathan Mak and myself who took equal share of the workload. Other contributions include amendments to laboratory procedure and analytic technique which were influenced by laboratory supervisor Fedja Orucevic.

## Context

This report seeks to evaluate the frequencies of the hyperfine transitions in a sample of natural rubidium containing both  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ . In addition, hyperfine linewidths and peak amplitude measurements will be quantified. Saturated laser absorption spectroscopy is the process of negating the effects of Doppler broadening via the use of a split beam where one is used to saturate a specific energy level in a material such that only zero velocity atoms can affect the absorption of the second beam. We find that saturated absorption spectroscopy is highly applicable when identifying the hyperfine transitions of a sample since using basic laser absorption spectroscopy produces peaks that have a linewidth that obscures these small transitions. Throughout this paper the term  $\Delta\nu_{FSR}$  is used to denote the 'Free Spectral Range' of the Fabry-Perot interferometer.

## Basic Laser Absorption Spectroscopy

A laser diode was used to produce a laser of variable frequency, this laser was split, where one beam is the input of a *Fabry-Perot Interferometer* which outputs to a photodiode as **Channel 2** on the oscilloscope[1], producing evenly spaced maxima. The other "probe" beam is directed through a sample of natural rubidium (containing  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ ) and then into a photodiode as **Channel 1** on the oscilloscope. When the frequency of the laser approaches the atomic transitions of the sample, four Gaussian peaks are observed, as the laser is absorbed more, with linewidth significantly greater than the natural linewidth of hyperfine transitions due to the Doppler broadening effect observed at temperatures as high as  $50^\circ\text{C}$ [2].

## Saturated Laser Absorption Spectroscopy

Using the same equipment set up as in [Basic Laser Absorption Spectroscopy](#) but splitting the previous probe beam again into a "probe" and a "pump" where the pump has a higher intensity than the probe. Counter-propagating these lasers through the rubidium sample such that they experience significant overlap produces saturation of hyperfine transitions when a resonance is observed. This saturation causes *hole burning* in the Gaussian profile as the pump beam saturation only affects the probe beam's absorption for stationary atoms (or atoms with velocities directly between two transitions called *Crossover Resonances*[3][4][5]) so this eliminates the effects of Doppler broadening. Tuning this signal with the output of the [Basic Laser Absorption Spectroscopy](#) using a subtraction operational amplifier allows the oscilloscope to observe only these transitions.

## Fabry-Perot Calibrations

As the oscilloscope's horizontal axis measures time, a calibration is used to convert this into frequency domain. Using the spectra observed from the [Saturated Laser Absorption Spectroscopy](#) the relative frequency of the different atomic transitions can be expressed in terms of how many Fabry-Perot maxima they are separated by. Continuing this by cross referencing them against the expected atomic transition frequencies, it is possible to calculate values for  $\Delta\nu_{FSR}$ . Which can be compared with the other transitions in the spectrum on a weighted mean to produce a calibration factor comparing the expected  $\Delta\nu_{FSR}$  against the calculated value.

## Results

Throughout the experimental procedure, measurements were made for the relative frequencies of each of the hyperfine transitions in rubidium (isotopes  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ ) as well as their relative absorption and linewidths. These quantities were also observed for the Doppler broadened spectrum.

Using the accepted relative frequencies in the literature, we compared the Fabry-Perot spectral range given in the instructor's manual[1] to the atomic transitions we observed[6][7], this resulted in the production of a calibration factor that was used to produce a reliable estimate for the spectral range of the Fabry-Perot interferometer. Comparing multiple relative frequencies created an accepted calibration factor of  $(1083.48 \pm 0.47) \times 10^{-3}$  which produced an expected Fabry-Perot spectral range of  $411.72 \pm 0.18$  MHz instead of the 380 MHz listed in the instructor's manual[1]. This calibration factor was used to compare the relative frequency of the  $^{87}\text{Rb} F = 2 \rightarrow ^{87}\text{Rb} F = 1$  peaks which have an expected separation of 6834.70 MHz. When the data is calibrated using the factor, the value measured deviates from the accepted value by  $15\sigma$ . This indicates that the calibration factor is not consistent with the expected behaviour of the Fabry-Perot interferometer and further analysis needs to occur in order to accurately measure the hyperfine transitions without the need for literary comparisons which need verification of their own.

The significance of these results is displayed through the confirmation of the predictive power of the theoretical understanding of the atomic hyperfine transitions as well as its applications to lasers and photonics to produce intuitive methods of calibrating frequency axes with reference to known atomic transitions.

Although deviating from expected values of these transitions this provides a further foothold to probe the reasons what phenomena had caused this scenario to occur as it should be due to a lack of consideration of control variables or systematic error that was unaccounted for. Errors that had been accounted for include the temperature of the rubidium sample which was kept at a near constant  $50^\circ\text{C}$  as well as the background luminosity of the room, as all of the laser apparatus was stored within a dark container. Contemplated sources of error include, the ambient pressure in the laboratory which could potentially lead to different broadening effects imposing on our results. Also the human error introduced via the manual calibration of the peak of each Fabry-Perot maximum would likely have produced a significant amount of systematic error that is unaccounted for in the results. The largest source of error that was unable to be corrected was due to the non-linearity (between voltage and frequency) of the piezo mechanism used to control the laser diode cavity length. This is the mechanism that causes the Fabry-Perot maxima to be unevenly spaced and even vary over different laboratory sessions. If the piezo function was measured and parameterised before the hyperfine transitions were measured, this could potentially be accounted for however, with the given equipment there was no established, reliable method to achieve this within the given time period.

This experiment leaves many different avenues for continuation and improvement. Such as the continued investigation into how the negative amplitude peaks behave under different optical parameters, perhaps to go as far as to simulate the pumped states occupation using the Clebsch-Gordan Coefficients to determine the transition probabilities. An improvement in the current experiment would be to produce a function which describes the relationship between voltage and frequency that the laser diode follows and parameterise it such that the calibration of the states (assuming no mode hopping) can be correctly mapped into the frequency domain without the requirement of the value described in the instructors manual.

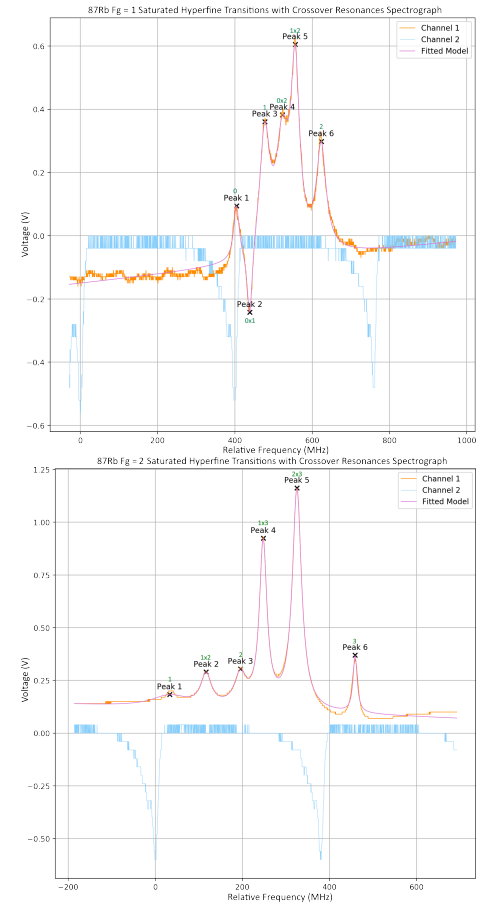
## Review

From this experiment we have parameterised the hyperfine transitions as well as the crossover resonances and produced reasonable cause to investigate further as to the unexpected behaviour of the Fabry-Perot interferometer measurement. This analysis yielded several measurements including the fits of the Doppler free hyperfine transitions, where the deviation from the model for each of the fits was in the order of microvolts for all four of the fits, in increasing frequency they were  $174\ \mu\text{V}$ ,  $8.72\ \mu\text{V}$ ,  $105\ \mu\text{V}$ ,  $227\ \mu\text{V}$ . The measurement for mean Fabry-Perot  $\Delta\nu_{\text{FSR}}$  was  $411.72 \pm 0.18$  MHz.

These values are very significant for both theoretical and practical reasons since many of modern technologies rely on the atomic transitions of hydrogen-like elements, one example being the caesium clock that is the current standard used to measure time, this time period is related to the linewidth of the atomic transitions. As well as the theoretical confirmation that the predictions do correlate with what is observed in the laboratory. Further measurements could be expanded to measure the hyperfine transitions of other elements or to probe deeper into what causes the negative peaks in some transitions.

## REFERENCES

1. D. C. Sinclair, "Fabry-perot cavity fp1-a instructor's manual," TeachSpin Inc. (2007).
2. J. Dunningham and I. Iliev, Atomic Physics Lecture Series, University of Sussex Dept. MPS (2018).
3. W. Demtroeder, *Laser Spectroscopy* (Springer New York, 1982), 4th ed.
4. Anon, "Saturated absorption spectroscopy," University of Florida Dept. Physics (2014).
5. D. W. Preston, "Doppler-free saturated absorption: Laser spectroscopy," California State University Dept. Physics (1996).
6. D. A. Steck, "Rubidium 87 d line data," Los Alamos National Laboratory (2001).
7. D. A. Steck, "Rubidium 85 d line data," Los Alamos National Laboratory (2001).



**Fig. 1.** Depicts the raw data observed in the hyperfine transitions of Rubidium 87 as well as the fit used to estimate the parameters of the peaks. Notice that one of the peaks in the  $F=1$  transition (top) has a negative amplitude.