Observation of Hyperfine Splitting in the Ground States of Rubidium Isotopes via Saturation Spectroscopy

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Abstract

This experiment aims to measure the hyperfine splitting of the ground states of ^{85}Rb and ^{87}Rb by measuring the transitions to their $5^2P_{3/2}$ excited state, which is denoted by F′. These transitions can be observed as Doppler broadened peaks when sweeping the frequency of a laser beam — the probe — through a rubidium gas cell. Higher precision can be reached using saturation spectroscopy, where at resonance, a pump beam depletes the ground state of the atoms capable of interacting with the probe. Using the former method, the voltage as a function of time was fitted to Gaussian distributions at the location of the four observed Doppler broadened peaks. The full width at half maximum (FWHM) of each voltage dip was found to be ^{87}Rb (F=2 → F′): $(3.84 \pm 0.06) \times 10^{-4}$ s, ^{85}Rb (F=3 → F′): $(3.20 \pm 0.07) \times 10^{-4}$ s, ^{85}Rb (F=1 → F′): $(2.98 \pm 0.06) \times 10^{-4}$ s, and ^{87}Rb (F=1 → F′): $(4.2 \pm 0.1) \times 10^{-5}$ s, corresponding to the four expected energy level transitions in the rubidium isotopes.

Contents

1 Components completed thus far

- Observed 2 Doppler-shifted transition peaks for each rubidium isotope and tuned the laser for a mode-hop-free observation.
- Got a rough, experimental setup for using both the pump and probe beams
- Made a coarse observation of hyperfine splitting in some of the Doppler broadened peaks (Note: we had issues interacting with the GUI and could not save data from this observation, so it is missing from this report).

2 Planned Measurements

- We plan to refine the mirror positions using the camera and LCD monitor to perfect the position of our probe beam
- The attenuation of the current and diffraction grating sweeps needs to be perfected to get the longest mode-hop-free run possible.
- We want to construct a Michaelson interferometer to calibrate our observations to the wavelength of the laser. This will allow us to record the laser frequency as the sweeps are done.
- We want to use the differential amplifier to remove the intensity dependence on the sweeps to isolate the frequency-dependent behaviour of the peaks.
- Time permitting, we want to vary the temperature of the rubidium gas chamber to observe the temperature dependence of the velocity distributions being observed.

3 Hypothesis and theory

Hyperfine splitting is caused by the different interactions between an atom's nucleus's magnetic dipole and the electron's magnetic moment. This results in splitting the atom's energy levels into multiple closely spaced levels. For instance, in rubidium, the ground state is split into two levels on the order of 1 GHz apart, while the first excited state, $5^2P_{3/2}$, is split into four levels on the order of 0.01 to 0.1 GHz. Since the ground state splitting is orders of magnitude larger than the excited splitting, it is much easier to observe experimentally [1].

In this experiment, we investigate the atomic transitions in rubidium (^{85}Rb and ^{87}Rb) between the two split ground states and the excited state (of both isotopes) using diode laser absorption spectroscopy. We can observe Doppler-broadened absorption profiles by directing a tunable laser beam through a vapour of rubidium atoms and measuring the transmitted light with a photodiode. These profiles reveal information about the atoms' energy levels and velocity distributions [1].

When laser light of frequency ν_L passes through the rubidium vapour, atoms absorb the light if the photon energy matches the energy difference between the two atomic states, which reduces the intensity of the light detected by the photodiode (see Figure). However, due to the thermal motion of the atoms, the observed absorption frequencies are Doppler-shifted depending on the atom's velocity v along the beam axis [2].

This broadening follows a Maxwell-Boltzmann distribution, where the number of atoms in a given velocity range dv is given by:

$$dn(v) = \sqrt{\frac{m}{2\pi k_b T}} \exp\left(\frac{-mv^2}{2k_b T}\right) dv, \tag{1}$$

where m is the mass of the rubidium atom, k_B is Boltzmann's constant, and T is the temperature of the vapor [1]. Eventually, these probe beams can be complemented with a pump beam of much higher intensity in the other direction to circumvent the Doppler broadening and resolve rubidium's hyperfine structures. This is achieved because the pump and probe beams interact with atoms on opposite sides of the velocity distribution except at resonance, where both beams interact with atoms having $v \approx 0$ along the beam direction. When this

occurs, the pump beam depletes the ground state of the atoms with $v \approx 0$ due to its high intensity, allowing minimum absorption of the probe. This is seen as a sharp peak within the Doppler-broadened features [1].

The experiment involves sweeping the laser frequency by connecting a ramp generator to the current source and using the piezoelectric component to control the diffraction grating position of the laser. The change in the photodiode's output on the other side of the gas chamber as a function of time was measured, which, in this setup, is implicitly a function of the laser frequency. As the laser frequency sweeps through resonance, the absorption lines for each rubidium isotope at their relevant transition states become visible. These absorption curves were fitted to Gaussian functions:

$$V(t) = V_0 \exp\left(\frac{-(t-t_0)^2}{2\sigma^2}\right), \tag{2}$$

and σ was used to find the full-width-half-maximum (FWHM) of the curves, as FWHM= $2\sigma\sqrt{2ln2}$. The observed FWHM values were compared to the theoretical Doppler-broadened widths, which were calculated based on Equation 1 using the fixed temperature of the chamber at 318.75 K and the known atomic mass of ^{85}Rb ($1.409993199 \times 10^{-25}$ kg) and ^{87}Rb ($1.44316060 \times 10^{-25}$ kg) [3]. Since the data was collected as a time series, the values were adjusted by multiplying by the central frequency of the laser (780 nm). This resulted in theoretical FWHM values of 0.0003245 s for ^{85}Rb and 0.0003207 s for ^{87}Rb.

The following FWHM values were calculated from the fits: ^{87}Rb (F=2 $\rightarrow$ F′): $(3.84 \pm 0.06) \times 10^{-4}$ s, ^{85}Rb (F=3 $\rightarrow$ F′): $(3.20 \pm 0.07) \times 10^{-4}$ s, ^{85}Rb (F=1 $\rightarrow$ F′): $(2.98 \pm 0.06) \times 10^{-4}$ s, and ^{87}Rb (F=1 $\rightarrow$ F′): $(4.2 \pm 0.1) \times 10^{-5}$ s. These are compared to their theoretical values in Fig. 1 c). The chi-square values obtained for these fits are -0.84, 8.91, 2.45, and -0.78, respectively. The high percent residuals in the fits, as seen in Fig. 1 b), are largely due to the chosen slices of data for each fit (these can be seen shaded in grey in panel a)). Taking larger slices results in non-Gaussian portions of data being included in the fit and, thus, a higher percent difference between fit and data. On the other hand, taking the slices to be too small makes it harder to fit the peaks to Gaussian functions, resulting in less accurate fits.

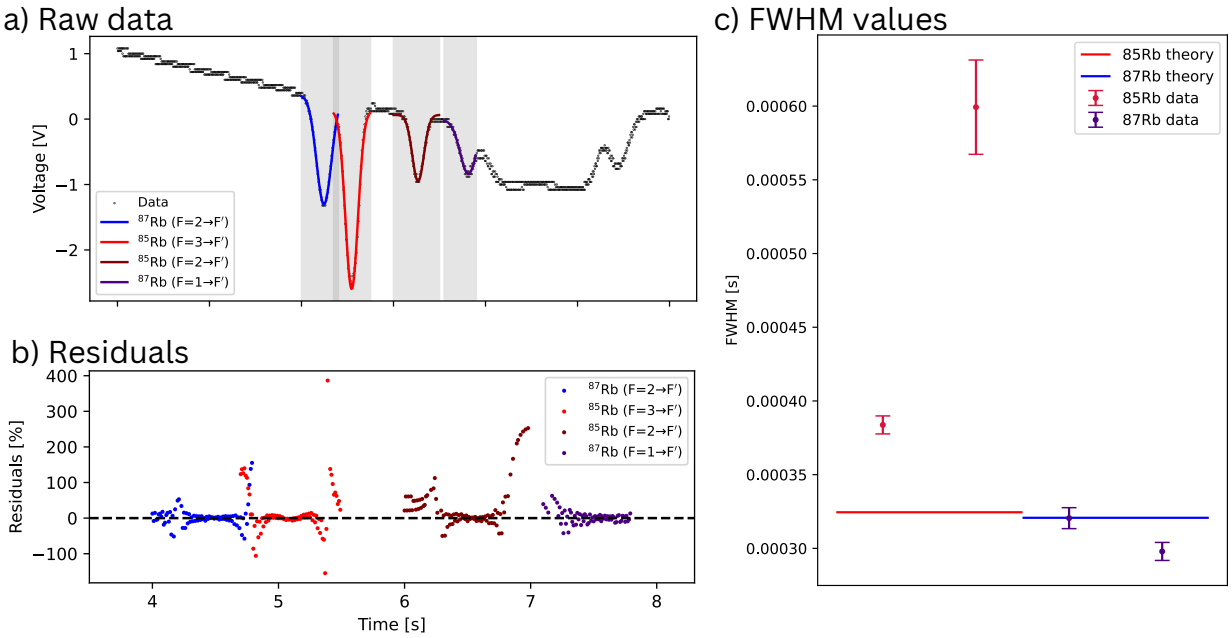

Figure 1: Observed Doppler-broadened absorption spectra of ^{85}Rb and ^{87}Rb. Each peak was fitted independently to a Gaussian curve in panel a), with residuals for the fits shown in panel b). Panel c) shows the computed full-width-half-max (FWHM) values for each fit, compared to the theoretical values computed using equation 1. Error bars on the data are too small to be seen in panels a) and b).

Many sources of uncertainty and error will be improved in the second stage of this experiment. The correction of multiplying the FWHM by the laser's central frequency needs to be more accurate, as we need to know that it is the central frequency within the range being probed. Instead, using a Michaelson interferometer will allow the time-series data to be more reliably converted to frequency space. Furthermore, the method used to vary the laser frequency also results in the laser intensity being varied, resulting in the overall slope observed in panel a) of Figure 1, which can be corrected using a differential amplifier.

References

[1] *Saturation Spectroscopy Lab Manual*. McGill Department of Physics. 2, 3

[2] M. S. Feld and V. S. Letokhov, "Laser spectroscopy," *Scientific American*, vol. 229, no. 6, pp. 69–85, 1973. [Online]. Available: http://www.jstor.org/stable/24923267 2

[3] A. L. Wyngaard, "Saturated absorption spectroscopy of rubidium and feedback control of laser frequency for doppler cooling," Ph.D. dissertation, Cape Peninsula University of Technology, 2018. 3