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## **Saturated absorption spectroscopy of $^{87}\text{Rb}$ : Toward a magnetic trap for cold collision studies**

### **Abstract**

An optical scheme using Doppler free saturated absorption spectroscopy was set up using four tunable external cavity diode lasers. The lasers will be used to magnetically trap  $^{87}\text{Rb}$  and then image collision reactions with cold molecules. Doppler free saturated absorption spectroscopy is explained, as well as a technique for locking the diode lasers. Acoustic-optical modulators are also described.

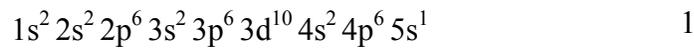
### **Motivation and Background**

In the Lewandowski lab we study interactions between cold atoms and cold molecules at temperatures of a few Kelvin and below. We are interested in studying atoms and molecules at these temperatures because we have more control over the particles and we are able to more easily observe them. Furthermore, we can learn about physics that happens in the interstellar medium which is also in this temperature range. In order to study collisions between molecules and atoms in the cold regime, we employ a variety of methods to slow down and trap the particles. Polar molecules, such as  $\text{NH}$ , are slowed using a Stark Decelerator, a method that employs time varying electric fields, which result in molecules climbing potential hills and losing kinetic energy as they travel the length of the apparatus. At the end of the decelerator the molecules are trapped in an electric trap. The atoms, which in our case are  $^{87}\text{Rb}$ , are slowed using lasers and magnetic fields. First, the  $\text{Rb}$  is slowed using a magneto-optical trap, which use the momentum of the photons in a laser, tuned to a frequency corresponding to a cycling transition, to slow the  $\text{Rb}$  and move it towards the center of the trap. Next, the atoms are moved to a magnetic trap, which is translated across an optical table to the electrically trapped  $\text{NH}$  so that the  $\text{Rb}$  and molecules can collide.

We use four diode lasers as well as accompanying optics to trap and image  $^{87}\text{Rb}$ . This summer, I setup the optics for two of the lasers, realigned the existing optical set up for the other two lasers, and locked the laser to frequencies corresponding to transitions in the hyperfine structure of  $^{87}\text{Rb}$ .

### Atomic Structure of $^{87}\text{Rb}$

To trap and image  $^{87}\text{Rb}$  we need laser light that is tuned to a hyperfine transition in the atomic structure. To understand the hyperfine structure it is advantageous to start by looking at the overall structure of Rb. The ground state configuration of Rb is



When the outer 5s electron is excited, it enters the 5p orbital, which is further split into 2 “fine” states,  $5p_{1/2}$  and  $5p_{3/2}$  (Figure 1). This fine splitting is due to spin-orbital interaction. In the spin-orbital interaction the electron, with charge  $e$  and mass  $m$ , has magnetic moment,  $\mu_e$ , which is due its spin ( $S$ ).

$$\mu = -\frac{e}{m} * S \quad 2$$

From the electron’s frame of reference, the charged nucleus is orbiting it with a velocity  $v$ , producing a magnetic field which interacts with the magnetic dipole of the electron. Torque is exerted on the magnetic moment of the electron by the magnetic field, causing the fine splitting of the energy levels. [1]

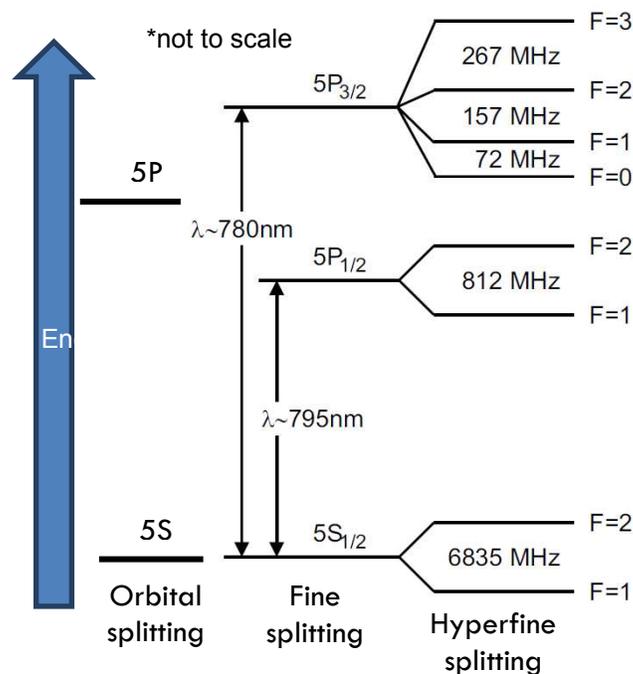


Figure 1. Atomic structure of  $^{87}\text{Rb}$ , with increasingly fine structure moving from left to right. The level separations are not to scale. [2]

Within each of the fine states there is further splitting known as “hyperfine splitting”. The proton in the nucleus also has a magnetic dipole moment, though it is smaller than that of the electron due to its larger mass. The two dipoles interact in what is known as a spin-spin coupling, resulting in the hyperfine splitting. For my experimental setup, I use the transitions between the hyperfine levels of  $5S_{1/2}$ , which are referred to as  $F = 1, 2$ , and hyperfine levels of  $5P_{3/2}$ , referred to as  $F' = 0, 1, 2, 3$  to lock the lasers.  $\mathbf{F}$  is the total angular momentum of the atom, consisting of the electron angular momentum ( $\mathbf{J}$ ) and the nuclear angular momentum ( $\mathbf{I}$ ). [1]

$$\mathbf{F}=\mathbf{I}+\mathbf{J}$$

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## External Cavity Diode Lasers

### *Theory of Operation*

We used Vortex and Vortex II external cavity diode lasers manufactured by New Focus, with a central wavelength of 780nm. Our external cavity diode lasers are based on the Littman-Metcalf design and use a laser diode chip with an anti-reflective coating, culminating lens, diffraction grating and retro reflector (Figure 2). The light leaves the laser diode chip and passes through the culminating lens. It is next incident on a diffraction grating where the negative first order diffracted beam travels to a retro reflector mirror and is then sent back to the laser diode as feedback. The position of the mirror pivots about a point, and is controlled by changing the voltage on the piezo-electric tuner (PZT). Rotating the mirror about the pivot point allows for wavelength tuning. Light from the diode, consisting of a range of wavelengths, reflects off the diffraction grating at different angles. By changing the angle of the retro reflective mirror, the user can select the desired wavelength of light sent back to the laser diode to be amplified within the cavity. The zero-order beam from the diffraction grating is the light that makes up the output of the laser [3].

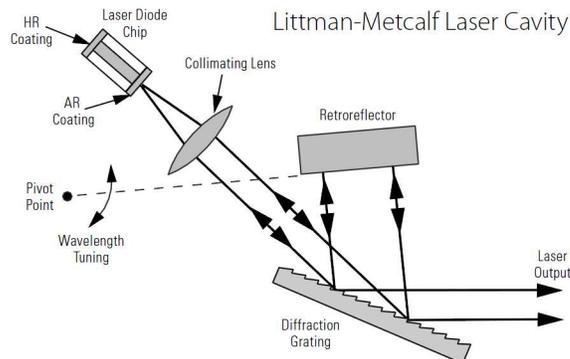


Figure 2. Diagram of Vortex laser cavity [4]

## *Application*

To slow and trap the  $^{87}\text{Rb}$ , three different wavelengths of light are needed, each corresponding to a different hyperfine transition in Rubidium. A fourth laser is necessary to image  $^{87}\text{Rb}$  during the experiment. The magneto-optical trap (MOT) trapping laser is tuned to the  $F = 2 \rightarrow F' = 3$  transition which acts as the cooling transition in the magneto-optical trap. In fact, the MOT laser frequency is tuned to be slightly less than this transition so that only Rb atoms moving towards the laser in the MOT will absorb the blue-shifted light and reemit it in a random direction. The process of pumping the Rb up to the  $F' = 3$  state continues until instead of falling to the  $F = 2$  state, the Rb enters the  $F = 1$  state where the MOT laser can no longer act on it. The re-pump laser, which is tuned to the  $F = 1 \rightarrow F' = 2$  transition, is thus needed to pump the Rb out of the  $F = 1$  state up to the  $F' = 2$  state, where it can re-enter the cycling transition and be further cooled. The third trapping laser is referred to as the  $2 - 2'$  laser, and it is tuned to produce light at a frequency corresponding to  $F = 2 \rightarrow F' = 2$  transition. This laser is used to pump the Rb in the MOT into the  $F' = 2$  state before it is transferred to the magnetic trap, because the  $F' = 2$  state has a more favorable Zeeman shift which corresponds to a deeper magnetic trap. Lastly, the probe laser is tuned to the  $F = 2 \rightarrow F' = 3$  transition, which is used to image the Rb in the magnetic trap as it is interacting with a molecule, such as NH [2].

## **Experimental Set-up**

### *Optical set up for Doppler Free Saturated Absorption Spectroscopy*

All four of the diode lasers use Doppler free saturated absorption spectroscopy in order to lock the laser to a hyperfine transition. The main components of this optical setup are a beam splitter, Rubidium gas cell, gold mirrors and a balanced photo-detector. A schematic of the layout can be seen in Figure 3. At the output of the diode laser is an opto-isolator which prevents light from being reflected back into the laser cavity, which would cause the laser to become unstable. The next element in the optical setup is a half wave plate, which changes the polarization of the light as desired. A polarizing beam splitting cube (PBS) follows the wave plate, splitting the light into two beams of orthogonal polarization, with part of the light going to the saturated absorption spectroscopy setup. The diode lasers output anywhere from 8 to 12 mW of power with the current set to the maximum allowable value. The saturated spectroscopy set-up

requires at most 1mW, which can be achieved by rotating the wave plate to attenuate the beam and measuring the power out of the side of the polarizing beam splitting cube with a power meter.

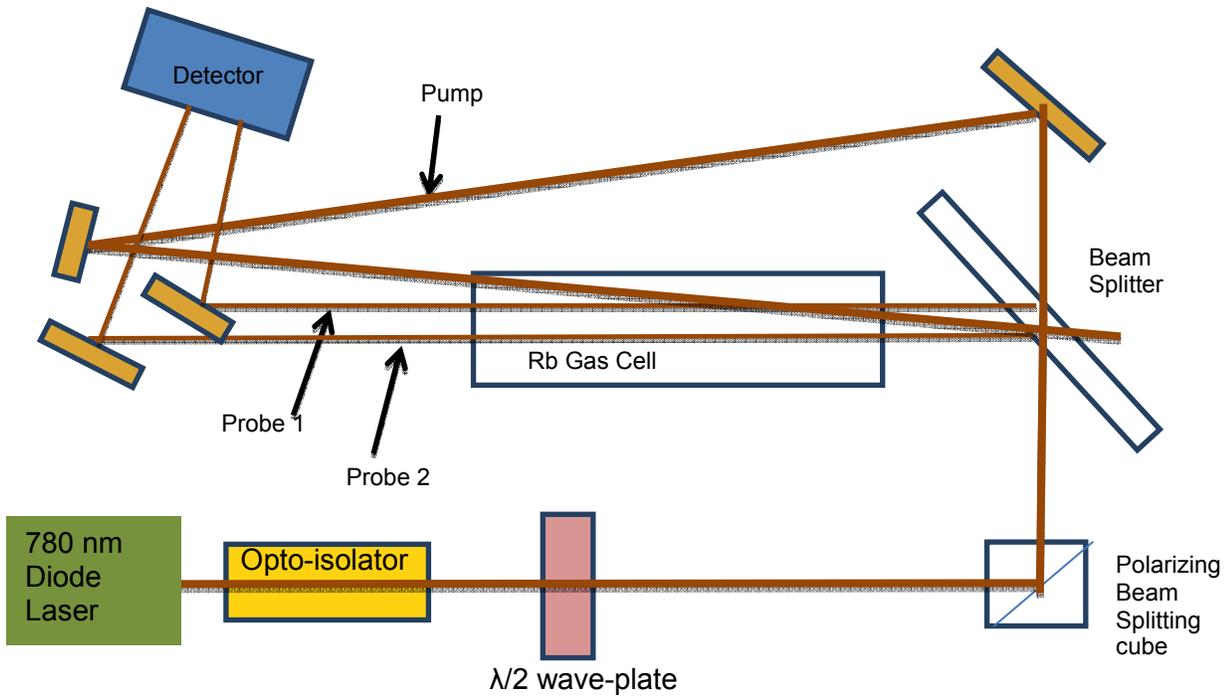


Figure 3. Optical set-up for Doppler free saturated absorption spectroscopy

Once the light enters the saturated spectroscopy setup it passes through a beam splitter, a 3/8 inch piece of glass positioned at an angle relative to the beam. The beam splitter reflects two weak, parallel beams, denoted “probe 1” and “probe 2,” off its front and back surfaces. The majority of the light passes through the beam splitter; this light is labeled the “pump” beam. The two probe beams next pass through the Rb gas cell, where the Rb can interact with the laser light at certain resonant frequencies. After passing through the gas cell, the probe beams are reflected off gold mirrors and focused into two photodiodes that together make up the balanced photo detector. The balanced photo detector subtracts the signal of probe 2 from that of probe 1, and then converts that signal to a voltage, which is displayed on an oscilloscope.

The pump beam passes through the beam splitter, is reflected off two gold mirrors so that it propagates through the gas cell in the opposite direction of the two probe beams. The pump beam is aligned so that it counter propagates along the same path as probe 1. The pump beam is much more powerful than the two probe beams [5].

## Observing the Doppler-free Saturated Absorption Spectroscopy

### *Doppler Broadened Peaks*

To observe the hyperfine transitions on the oscilloscope, I started by finding the Doppler broadened absorption peaks which are evidence of the fine structure of Rb. Initially, I blocked the pump beam, as well as probe 2, so that only the signal from one of the probe beams was observed. The PZT was ramped with a 20 V peak-to-peak triangle wave driven at a frequency of 22 Hz. Additionally, a DC voltage offset of approximately 50V was applied in order to sweep the laser frequency in the range that corresponds to the transition between the  $5P_{1/2}$  and  $5P_{3/2}$  states. To determine the specific offset voltage, I adjusted the DC voltage offset applied to the PZT using the knob control on the laser head controller until the Doppler broadened absorption peaks became visible (Figure 4.a).

The hyperfine structure of Rb would show absorption at only the resonant frequencies between hyperfine states,  $\nu_0$ . The hyperfine structure is not visible due to the Doppler shift of the laser light (Eqn. 2). Light is absorbed for non-resonant frequencies,  $\nu_L$ , depending on the velocity of the Rubidium atom relative to the laser,  $V_z$ , as described by the Doppler equation, with  $c$  being the speed of light in a vacuum [4].

$$\nu_L = \nu_0(1 + V_z/c)$$

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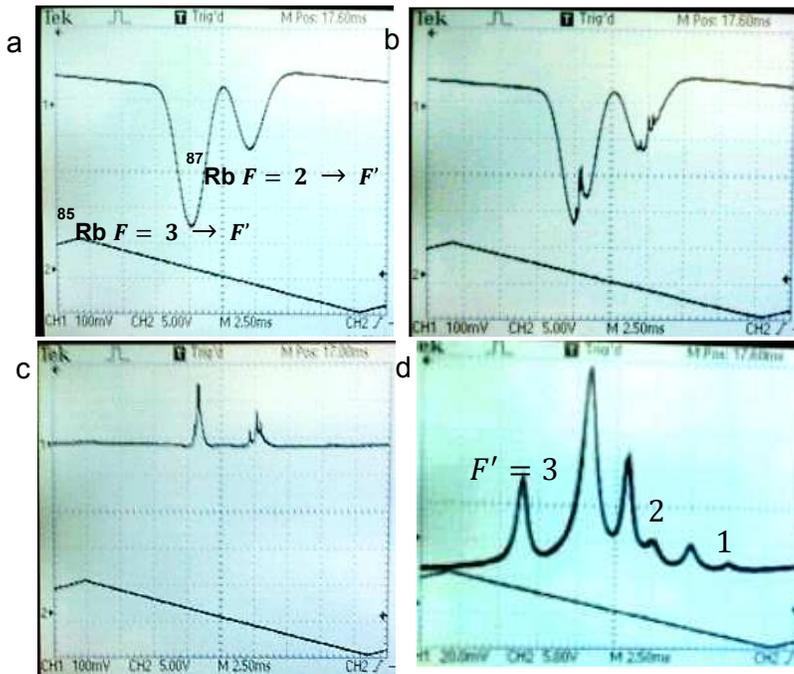


Figure 4. a). Doppler broadened peaks seen when only observing signal from probe 1. Triangle wave is ramped voltage applied to PZT to sweep different frequencies. b). Hyperfine structure riding on Doppler broadened peak. Probe 1 signal with probe beam overlapping. c). Doppler broadened peaks subtracted out by allowing probe 2 to enter balanced photodetector, leaving only hyperfine structure. d). Close up of  $F=2 \rightarrow F'$  hyperfine transition. Crossover peaks are also visible.

There exist four Doppler broadened peaks for Rubidium, though only two are visible in Figure 3.a. Two of the four the peaks are transitions between the  $5S_{1/2}$  and each two  $5P$  states for  $^{85}\text{Rb}$ , and the other two represent the same transitions, but for  $^{87}\text{Rb}$ .

### *Doppler-free peaks*

Once the Doppler broadened peaks are located I can observe the hyperfine peaks by unblocking the counter propagating pump beam. (Figure 4.b). The pump beam is at the same frequency as the probe beam, and thus is absorbed by Rb when it passes through the gas cell. The probe 1 beam passes through the exact same region as the pump beam, but since some of the Rb is already in the excited state there is less in the ground state to absorb the probe beam. Consequently, more photons from the probe beam arrive at the photo detector, causing the peaks that are visible in Figure 4.b since the pump and probe beams are counter-propagating the only atoms that both lasers can interact with at the same frequency are those with zero velocity in the direction of propagation of the photons. There is no Doppler broadening of the hyperfine structure which is visible riding on the larger Doppler broadened peaks. To make the hyperfine lines easier to distinguish, probe 2 is unblocked. The photo detector subtracts the Doppler broadened signal probe 2 from that of probe 1, leaving only the hyperfine structure (Figure 4.c)

Figure 3.d shows the hyperfine structure of  $^{87}\text{Rb}$  for the transition  $F = 2 - F'$ , with six peaks visible. There are three labeled peaks that correspond to transitions in the hyperfine structure. The three other peaks are known as “cross-over” peaks, and occur exactly halfway between the non-crossover peaks. The tallest peak is the crossover peak between  $F' = 2$  and  $F' = 3$ . At the frequency halfway between two resonant frequencies, Rubidium atoms moving with a certain nonzero velocity will see the light from one of the beams red shifted exactly half the difference between the two resonant frequencies. This same atom will also observe the light from the other laser to be blue shifted by exactly the same amount, and will thus be resonant with that transition too. Both lasers can be absorbed by the Rb atoms at this frequency, and therefore there is a decrease in absorption of the probe beam at the crossover frequencies, creating peaks in the signal. These cross over peaks are a very useful tool in locking the laser because they are larger and can be easier to lock to. [5]

## *AOMs*

Three of the four lasers are locked to crossover peaks and then frequency shifted to the hyperfine transition frequency using an acousto-optic modulator (AOM). AOMs consist of a transparent crystal, such as quartz, with an acoustic absorber on one side and a piezo-electric transducer (PZT) on the other. The PZT oscillates at a frequency,  $F_o$ , between 40 and 400MHz, creating a phonon that propagates inside the crystal. A phonon can be thought of as the matter equivalent to a photon, carrying momentum and propagating through a medium. As the laser passes through the crystal the photons combine with the phonons to either increase or decrease the frequency of the incoming laser light,  $\nu_o$ , by  $F_o$ , as described by the following equation with  $m$  being the diffraction order

$$\nu = \nu_o + mF_o$$

The positive first order diffracted beam ( $m=1$ ) is diffracted away from the PZT at an angle which is dependent on  $F_o$ , gaining the frequency of the phonon. The frequency of the AOM is set to match the well-known frequency difference between the crossover peak and hyperfine transition, in order to shift the frequency of light by the desired amount. The AOMs also act as fast shutters in the optical set-up, because deflected beam is turned off when the AOM is turned off, a process much faster than blocking the beam with a mechanical shutter. [2]

## **Locking the Laser**

To successfully trap and image Rb the diode laser must be locked to a specific frequency, which in our case corresponds to one of the peaks in the hyperfine structure. To lock the laser to the peak the derivative of the signal, with respect to time, must first be produced. If the derivative signal is not taken, there is no way to know what side of a peak the frequency is on, and thus there is no way to determine in which manner the frequency must be changed in order to reach the peak. The derivative signal, which acts as the error signal in the feedback loop, is calculated by sweeping that saturated spectroscopy lines at a rate of 50 KHz using the 50 KHz peak-lock box. The error signal can be viewed by connecting the “Set Point Monitor” output on the side-lock servo controller to the oscilloscope. Next, with the desired hyperfine transition peak centered on the oscilloscope screen, decrease the ramp gain of the triangle wave using the “Ramp Gain” knob on the side-lock servo. The “PZT Bias” knob can be adjusted while turning down the ramp gain to keep the peak in the middle of the screen. Once the gain is turned all the way down,

the peak will appear as a flat line across the oscilloscope at some non-zero voltage value, and the error signal should be at or near zero. When the error signal is zero, flip the switch marked “Ramp” to the off position, while also turning on the switch labeled “PZT loop” to the on position. This should lock the laser to the desired peak. [6]

### **Results and Further Work**

This summer I set up the optics for both the  $2 - 2'$  laser as well as the re-pump laser. Both lasers have been successfully locked and are ready to be used in the next stage of the experiment. The  $2 - 2'$  laser light not going to the saturated spectroscopy setup has been sent through an AOM to shift the frequency to the  $F = 2 \rightarrow F' = 2$  hyperfine transition from the crossover peak it is locked to. The re-pump laser is locked directly to the  $F = 1 \rightarrow F' = 2$  hyperfine transition, and thus does not use an AOM. The light from the re-pump laser that did not go to the saturated spectroscopy was fiber coupled. The MOT laser has also been successfully locked, though the optics are still in progress. The MOT trapping optical setup further consists of a slave laser and fabry-perot cavity that need to be realigned. The probe laser set-up utilizes two AOMs which took some effort to align. After the second AOM the light is fiber coupled, and I am still working on getting enough power in the deflected beam to be fiber coupled. The saturated spectroscopy lines for the probe laser are still too noisy to be locked to, and I am currently working on realigning that part of the optical setup. Although there are a few elements that still need work, overall this summer was very productive. We are well on our way to magnetically trapping and imaging  $^{87}\text{Rb}$ .

## References

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