Development of an Ultracold Rubidium-85 System for Magnetic Molecules and Feshbach Physics

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by

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Abstract

This thesis presents progress on a path to Rubidium-85 Feshbach molecules that could be used for magnetometery and other experiments. An apparatus including a magneto-optical trap, magnetic trap, and dual laser dipole trap has been modified for studies of the 155 G Feshbach resonance and associated production of ultracold Rubidium-85 molecules. Modifications include changes in the optical pumping technique to spin-polarize Rubidium-85 atoms in the F=2, m_F =-2 hyperfine state. In addition, we constructed a dual 6.8 GHz and 3.0 GHz source and a 3 GHz microwave amplifier to evaporatively cool Rubidium-87 and Rubidium-85 and allow for more control of the atomic spin. These modifications and techniques will aid in manipulating the atomic spins in future experiments. As an example, we perform microwave spectroscopy on Rubidium-85 atoms from which we infer a residual magnetic field in the MOT cell of 170±5 mG. We also found the $|F=2, m_F = 0\rangle \leftrightarrow |F=3, m_F = 0\rangle$ transition to have a Rabi frequency of $\Omega_R = 8.9 \pm 0.5$ kHz, the $|F=2, m_F = 0\rangle \leftrightarrow |F=3,$ $m_F = -1\rangle$ transition to have $\Omega_R = 10.1 \pm 0.5$ kHz, and the $|F=2, m_F = 0\rangle \leftrightarrow |F=3,$ $m_F = +1\rangle$ transition to have $\Omega_R = 11.0 \pm 0.5$ kHz.

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1 Introduction

Over the past twenty years advances in technology have allowed atoms to be cooled to temperatures near absolute zero, where they form Bose-Einstein condensates, a new quantum state of matter. Cooling atoms to these temperatures has opened the doors for many successful experiments on quantum control, atom interferometry, and many-body physics. Unfortunately, while atoms can be cooled to these temperatures, molecules cannot. However, it is possible to take ultracold atoms and essentially glue them together to form ultracold molecules. Being able to create and manipulate ultracold molecules opens up the possibility of studying ultracold chemistry, creating new quantum and superfluid gases, and make improved precision measurements of fundamental symmetries in nature.

This thesis describes progress towards creating ultracold Feshbach molecules with Rubidium-85 in Professor Seth Aubin's lab at William and Mary. To create the Feshbach molecules, Rubidium-85 atoms must be cooled to ultracold temperatures and loaded into a pure optical trap in the appropriate spin state. This thesis discusses the steps used to cool the atoms and polarize them in the appropriate spin state, including the development of a precision microwave source to be used to aid in these processes. We will then discuss a magnetometry experiment run with Rubidium-85 atoms.

2 Theory

2.1 Feshbach Resonance

Currently, molecules cannot be cooled directly to ultracold temperatures. However, it is possible to instead assemble ultracold atoms into ultracold molecules. Several techniques have been implemented to do this, but one very successful method is through use of a Feshbach resonance, a resonant enhancement in the scattering length of two atoms colliding at a particular magnetic field strength [1]. The scattering length is related to the effective radius of the collisional cross-section of an atomic collision (see Figure 1a). Near resonance B_0 , the scattering length a_s of an interaction for a resonance of width Δ is given by [2]

$$a_s = a_{bg} \left(1 - \frac{\Delta}{B - B_0}\right) \tag{1}$$

where a_{bg} is the background scattering length. A positive scattering length corresponds to a repulsive interaction, while a negative scattering length corresponds to an attractive interaction (Figure 1b). Ramping the magnetic field across the resonance in the appropriate direction causes the atoms to form weakly bound molecules, with binding energies generally measured in the MHz frequency range (Figure 1c). An advantage of this technique is that not only are ultracold molecules formed, but they are all formed in the same quantum state [2].

The scattering length is related to the collisional cross-section of the atoms. This can be understood by thinking of the collisions of atoms not in the frame of the lab, but in the reduced coordinate, and by considering the atoms as waves, not as particles (see Fig. 2). In this case, the problem can be thought of as a simple scattering problem of an incoming planar wave colliding with a spherical s-wave, an appropriate approximation if the atoms are cold. The outgoing wave can then be approximated as

$$\psi(x) \sim e^{ikz} + f(\theta) \frac{e^{ikr}}{r} \tag{2}$$

where z is the axis of propagation, and $f(\theta)$ is also the scattering amplitude of the particle. In this limit, the differential cross section is $\left|\frac{d\sigma}{d\Omega}\right| = |f(\theta)|^2$, so it is relatively easy to relate the scattering length to the collisional cross-section, σ , with an elastic collision approximation of hard spheres, and we find that

$$\sigma = 4\pi g_{\alpha} a^2 \tag{3}$$

where g_{α} is 1 in the case of nonidentical particles, 0 in the case of fermions, and 2 in the case of identical bosons, which we are using in this experiment. This collisional cross-section is a good way to detect the location of the Feshbach resonance because the increase in crosssection corresponds to an increase in atom loss from the trap. Thus, by imaging the atoms in the trap, there should be fewer atoms detected due to collisions near resonance, following the curve in Fig. 3.



Figure 1: Feshbach resonance for colliding ultracold atoms. (a) Atoms collide together and then scatter off of each other as described by (b) Feshbach scattering length a normalized to the background scattering length a_{bg} . (c) The binding energy Eb of molecules formed as the magnetic field is ramped from high to low, following the blue arrow, across the Feshbach resonance (adapted from [2]). (d) Feshbach molecules are formed in a barely bound state of the triplet potential but can then be transferred, when excited by lasers, up to a higher state and then down to the triplet ground state (adapted from diagram for KRb molecules [1]).

For the Feshbach resonance to be effective the atoms must all be in the appropriate spin state. In the case of the Feshbach resonance we would like to access, the atoms must be in the $|2,-2\rangle$ state, referring to the hyperfine state F = 2, and the m_F level -2. The hyperfine splitting is caused by the interaction between the spin of the electron and the spin of the nucleus. The nuclear spin of Rubidium-85 is I = 5/2 while for Rubidium-87, I = 3/2, so there are more hyperfine levels in Rubidium-85. We also want the Rubidium-85 atoms in the $|2,-2\rangle$ ground state, with the electron in the s-orbital.

The location and width of the Feshbach resonance varies depending on the properties of the particular atoms used to make molecules. Our lab works with four different atoms: Rubidium-85, Rubidium-87, and Potassium-40, and Potassium-39, and any combination could potentially be used to make Feshbach molecules. However, wider resonances are easier to detect, and there are constraints on the magnetic field strength the apparatus is currently capable of producing. Thus, we chose the Rubidium-85 F=2, $m_F=-2$ resonance because it



Figure 2: A collision between atoms can be thought of as a planar wave colliding with a spherical wave (adapted from [10]). An incoming planar wave in the z-direction has form e^{ikz} . The outgoing spherical wave has form $f(\theta)e^{ikr}/r$ where θ is the angle from the z-direction and ϕ is the azimuthal angle.

occurs at 155 G, a field that we can reach with our apparatus, and it is 11.65 G wide, wider than many other available resonances [10].

3 Trapping Rubidium-85

3.1 Overview of Apparatus: Cold Atom Recipe

Before creating ultracold molecules, the atoms must cooled to ultracold temperatures. A summary of the steps is shown in Fig. 4. The process is done in a glass cell (see Fig. 5) kept at ultrahigh vacuum. First the atoms are trapped in a Magneto-Optical Trap (MOT) at a temperature of approximately 60μ K. A MOT consists of 6 laser beams, 2 counterpropagating along each axis, and two coils in anti-Helmholtz configuration, parallel coils with equal currents running in opposite directions. The lasers are near resonance - about 780 nm for Rubidium - but slightly red-detuned from resonance, which allows for Doppler cooling, where atoms will preferentially absorb light and the corresponding momentum kick



Figure 3: Collisional cross-section vs. detuning from Feshbach resonance. The collisional cross-section is proportional to the square of the scattering length (see Fig. 1).

from the direction they are moving and thus will tend to slow down and become colder. However, these atoms can still diffuse: they are not trapped. The trapping occurs through use of the coils as well. At the center of the coils the field is zero, but the field increases as atoms move away from the center of the MOT. This means that through the Zeeman effect, the m_F levels split in energy. Due to the fact that the direction of the field is different on each side of the MOT, the negative m_F levels will have a lower energy than the positive m_F levels on one side of the zero field while on the other side the positive m_F levels will have a lower energy than the negative m_F levels. By making the counter-propagating beams have oppositely circularly polarized light, a slow atom in a low energy m_F level will be more likely to absorb light from the nearer laser beam with the appropriate polarization and will be kicked back towards the center of the MOT (see Fig. 6). This produces a spatially dependent trapping force.

Magnetic fields add energy to the trapping system, so once the atoms are trapped in a MOT, they are further cooled to 30μ K with purely optical cooling known as molasses cooling. Again the six counter-propagating laser beams are used, and Doppler cooling is still important, but another effect, known as sisyphus cooling, is important as well. Sisyphus cooling involves the creation of a polarization standing wave that alternates between linear, left-handed and right-handed circularly polarized light. Due to the AC Stark Effect, the



Figure 4: Overview of steps for cooling atoms. First atoms are trapped and cooled in a MOT. Then they are cooled further with molasses. From there they are optically pumped into the appropriate spin state, in this case $|2,-2\rangle$, and loaded into the magnetic trap. Then the atoms are evaporatively cooled using a microwave or radio frequency source before being loaded into the dipole trap.

different m_F levels shift in energy depending on the direction of circular polarization. Thus each atom, depending on its spin state will see a standing wave of potentials. An atom with a negative m_F level will see a minimum potential energy in a left-handed polarized light area and a maximum in a right-handed polarized light area. As the atom moves from an area left-handed light to right-handed light its potential energy will increase and its kinetic energy will decrease. However, it will also absorb more right-handed light, so its m_F levels will become positive through stimulated emission and it will be at a minimum potential energy. It will not regain the kinetic energy it lost when it climbed the hill. That will be carried away by the photon. This is an extremely effective way to cool atoms (see Fig. 7).

Once the atoms are cooled they are optically pumped to become spin-polarized and then loaded into a magnetic trap, where their temperature increases to 50μ K. The magnetic trap also uses the anti-Helmholtz coils and has a zero potential at the center of the trap and a field gradient on all sides that exerts a force counteracting the force of gravity and holding the atoms in the trap. This magnetic trap also allows for evaporative cooling. There are two mechanisms for evaporative cooling. The current method uses radio frequency signals to target the transition between m_F levels and manipulate spins into a lower, anti-trapped state. However, a new instrument has been developed to evaporatively cool atoms using



Figure 5: MOT and dipole trap setup. MOT cell surrounded by two anti-helmholtz coils (blue), six counter-propagating MOT beams (orange), and two dipole beams (red).

a microwave frequency. This is done by tuning a microwave source to a frequency that couples with the transition between two manifolds in the lower energy state. The excitation frequency corresponds to a frequency of 6.834682610 GHz for Rubidium-87 for transitions between the F=1 and F=2 states and 3.035732439 GHz for Rubidium-85 for transitions between the F=2 and F=3 states [9]. For this process, the atoms are held in a magnetic trap. Then a frequency sweep is applied that varies from well above resonance to just above resonance. The more energetic atoms that are capable of moving to higher potentials further from the center of the magnetic trap get spin flipped from the $|2,2\rangle$ state to the $|1,1\rangle$ state. which satisfies $\Delta m_F = -1, 0, 1$. In the lower, F=1 manifold, $|1,1\rangle$ is anti-trapped, so the atoms escape (see Fig. 8).

As a last step, the spin-polarized atoms can be loaded into a dipole trap for a final temperature of 7μ K. The trap is made using a focused 1064 nm laser. Since these atoms have a magnetic dipole moment and an inducible electric dipole moment, they will still be attracted to an area of maximum electromagnetic field. The laser is far detuned from resonance to prevent heating. There is another 1064 nm laser that has also been added



Figure 6: Simplified 3-level MOT trapping. In addition to doppler cooling, the magnetic field provides a trapping mechanism for the MOT. As the atom moves from the center of the trap, the Zeeman shift causes some m_F levels to favor red-detuned light. In this picture, the atom in the m_F =-1 state will absorb right-hand circularly polarized light and increase its m_F level. If the beam coming in from the right is right-hand circularly polarized, the atom will get a kick back towards the center of the trap.

to intersect the magnetic trap to make the current dipole trap denser, which will help in the creation of Feshbach molecules due to the increase in collision rate (see Appendix A). Rubidium-87 has been successfully loaded into the dipole trap. Rubidium-85 has as well, but not in large numbers. Once the atoms are spin-polarized and in the dipole trap the magnetic field can be swept across the Feshbach resonance. This way the constant magnetic field will not interfere with the trapping of the atoms.

3.2 Current Progress on Cooling Rubidium-85

Rubidium-85 has been successfully trapped in the MOT and loaded into the magnetic trap (see Fig. 9). The atoms have also been loaded into the dipole trap, though not in high enough concentrations in the appropriate spin state to apply a Feshbach resonance. The next two sections will discuss how we attempt to spin-polarize our atoms and how we will detect their polarization.



Figure 7: Sisyphus cooling. A standing polarization wave that varies between linear, lefthanded, and right-handed polarization. An atom with a negative m_F level will see a minimum potential energy in a left-handed polarized light area and a maximum in a right-handed polarized light area. As the atom moves from an area left-handed light to right-handed light its potential energy will increase and its kinetic energy will decrease. However, it will also absorb more right-handed light, so its m_F levels will become positive through stimulated emission and it will be at a minimum potential energy. It will not regain the kinetic energy it lost when it climbed the hill (figure adapted from [11]).

4 Spin Manipulation

Two main techniques are being used to try to spin-polarize Rubidium-85 in the $|2,-2\rangle$ state. The first technique is optical pumping, while the second technique is spin manipulation through use of a microwave source.

4.1 Optical Pumping

The most straightforward way to get all the atoms into the appropriate spin state is through optical pumping. Optical pumping works by directing resonant circularly polarized laser light onto the atoms. When the atoms absorb the light the electrons are excited to a higher energy level with an m_F level change of +1 or -1, depending on the direction of polarization. In this case, we want to trap in the $|2,-2\rangle$ state, so light acts in the -1 direction as shown in Fig. 10. When the atom emits a photon and returns to the lower energy state the m_F level will change by $\Delta m_F = 0, \pm 1$, so there is a bias for the atoms to tend towards the most extreme m_F state.

Rubidium-85 has the additional complication that it must be trapped in the F=2 level



Figure 8: Diagram of microwave evaporation with Rubidium-87. The splitting between the F=1 and F=2 fine structure levels for Rubidium-87 is approximately 6.8 GHz. Applying a magnetic field splits the fine structure levels and by sweeping a frequency from well above resonance to just above resonance, the more energetic atoms capable of moving further in the magnetic trap get spin flipped from the $|2,2\rangle$ state to the $|1,1\rangle$ state which satisfies $\Delta m_F = -1, 0, 1$. In the lower, F=1 manifold, $|1,1\rangle$ cannot be trapped, so the atoms escape.

but atoms could also be in the F=3 level. Thus atoms in the F=3 level must be depumped to the F=2 level. Thus there must be two lasers, one to optically pump the atoms in the F=2 state into the $|2,-2\rangle$ state and one to depump the atoms that are in the F=3 state into the F=2 state. These lasers are shown in Fig. 10.

We have not been able to successfully trap Rubidium-85 atoms in the $|2,-2\rangle$ state. However, we have been able to optically pump atoms into the $|3,3\rangle$ state, which is easier because it is a complete stretch state.

4.2 Microwave Manipulation

Another way to manipulate spins is to use a microwave frequency to target the hyperfine transition. Just as microwaves can be used in evaporative cooling in the magnetic trap, they can manipulate spins in the dipole trap, where there are no anti-trapped states. As such, since we can optically pump atoms into the $|3,+3\rangle$ state, it is possible to use a microwave



Figure 9: Fluorescence image of Rubidium-85 atoms in magnetic trap.

sweep to transfer them to the $|2,+2\rangle$ state, then back to $|3,+1\rangle$, then to $|2,0\rangle$, $3,-1\rangle$, and finally to the $|2,-2\rangle$ state. Another possibility would be to transfer the atoms to the $|2,+2\rangle$ state and then use radio frequency radiation to transfer the atoms to the $|2,-2\rangle$ state.

5 Spin Characterization

To see if our spin manipulation techniques are successful, we need to have a way to characterize our spins. We have developed one technique and are currently testing another technique to do this.

5.1 Spin Distillation

In order to create Feshbach molecules with ⁸⁵Rb we must first trap them in the $|2, -2\rangle$ state. Although it is relatively straight forward to trap the atoms using the MOT and molasses cooling by simply altering the resonance frequencies, making the atoms spin-polarized is more challenging. We made one attempt to use optical pumping to get the atoms into this state. The circularly polarized light from the laser used to pump the atoms in the F=2 state specifically to the $m_F = -2$ state was set at the transition from the $5^2S_{1/2}$ F=2 state to the $5^2P_{3/2}$ F=2 state. Then the trapping laser doubled as a repumper, moving the atoms from



Figure 10: Optical pumping of ⁸⁵Rb into $|2,-2\rangle$ state. Left: the depump laser moves atoms from F=3 to F=2. Right: the polarized pump laser moves atoms to $|2,-2\rangle$ state.

the $5^2S_{1/2}$ F=3 state to the $5^2P_{3/2}$ F=3 state (see Fig. 10). This was necessary to force all of the atoms from the F=3 state to the F=2 state. The repumper was left on for a very short period of time after the regular optical pump was turned off in order to ensure that the atoms were in the F=2 state.

After the atoms were supposedly in the F=2 state, they were magnetically trapped by applying a trapping field that would just counteract the force of gravity (see Fig. 9). Atoms in higher m_F states need lower field gradients to remain trapped (see Fig. 11). The maximum potential energy of the dipole moment of an electron in a trap is 1.4 Mhz·h/Gauss, although this gradient decreases with lower m_F states. To magnetically trap just the $|2 - 2\rangle$ atoms the magnetic force up should just counteract the force due gravity down. Given the mass of ⁸⁷Rb, the force due to gravity is 1.41×10^{-26} J/cm. Then the magnetic field gradient must be $(1.41 \times 10^{-26}$ J/cm)/(1.41 MHz×h×2/3)=22.7 Gauss/cm. Note that there is a 2/3 in the denominator because we are trying to trap the $m_F = 2$ state when there is also the $m_F = 3$ state, which has a gradient of 1.4 Mhz·h/Gauss. To trap $|2,-2\rangle$ means applying 52 A to the Helmholtz coils which have a response of 0.43 Gauss/(cm A).

We applied a range of currents to the Helmholtz coils. Unfortunately, there were still

atoms with a current significantly below 52A, meaning we were also trapping atoms in the $|3,3\rangle$ state (see Fig. 12).



Figure 11: Spin distillation technique. Different spin states have different potential energies for a given magnetic field strength in the magnetic trap. The potential due to the magnetic field counteracts the potential due to gravity assuming a sufficiently strong magnetic field gradient. By decreasing the magnetic field gradient (right), the potential can become negative and atoms will fall out of the trap. This occurs first for the lower m_F level states.



Figure 12: Spin distillation of ⁸⁵Rb. Atom number versus magnetic field gradient in magnetic trap. Error bars are standard deviation.

5.2 Stern-Gerlach with Rubidium-87

The spin distillation technique is effective but slow. A quicker mechanism to characterize spins is to run a Stern-Gerlach experiment with atoms trapped in the dipole trap. Since Rubidium-87 can be trapped with reasonable density in the dipole trap, it is possible to perform this experiment on the atoms, where atoms in different spin states will separate in a magnetic field gradient. The MOT coils provide the gradient, which is 0.86 G/cm·A, which with 97A of current corresponds to a gradient of 84 G/cm. However, the center of the MOT is near the dipole trap, so we need to use the push coils to provide a constant field that will shift the center of the MOT away from the dipole trap. The push coils provide a field of 2.1 G/A. The Rubidium-87 atoms were loaded from the magnetic trap into the dipole trap and thus should be spin-polarized in the $|2,-2\rangle$ state, although the loading mechanism could cause some spin-flips.

Once the atoms were trapped in the dipole trap, the dipole laser was turned off and the atoms fell in the gradient for 3 ms and then the gradient was turned off and the atoms were imaged after 1 ms. The results are shown in Fig. 13. There are clearly some atoms to the right of the dipole trap when the push coils are turned on. This direction corresponds to the direction of the center of the trap and the direction of decreasing field, which is the direction an atom with spin $|2,-2\rangle$ would move. However, the results are inconclusive, as tests with atoms in different spin states are necessary to confirm that we are correctly reproducing a Stern-Gerlach experiment.

6 Microwave Source and Amplifier

Evaporative cooling and spin manipulation with microwave frequencies requires a high precision microwave source. Although the lab already has a microwave source and amplifier designed to target Rubidium-87, we built an amplifier to target Rubidium-85 and a precision microwave source to control both the Rubidium-85 and the Rubidium-87 amplifiers.

6.1 Precision Microwave Source

The 6.8 GHz amplifier to target Rubidium-87 has been built previously, but the lab acquired a variable digital microwave source, the Windfreak SynthNV, that makes it easier to set



Figure 13: Preliminary Stern-Gerlach experiment with Rubidium-87. Magnetic field zero is near center of dipole trap and then moves to the right as the push coil field increases. With the increase of push coil field, a clump of atoms appears to the right, consistent with atoms in the $|2,-2\rangle$ state. Push coils and MOT coils on for 3 ms, and total time of flight is 4 ms.

the specific frequency (see Fig. 14). Its approximate frequency can be programmed using software and then that frequency can be swept by varying the frequency of an approximately 10 MHz external clock. This works with the caveat that the SynthNV contains multiple voltage controlled oscillators (VCOs), which allow for the frequency modulation. When the SynthNV is run without its software, it is programmed to a particular VCO, and will turn off its output if the frequency varies outside of the VCO's range. Thus, to do the appropriate scanning range for the 3.0 GHz source, the frequency must be set to 3.050 GHz, so that the upper bound necessary for evaporative cooling, 3.07 GHz, can be reached. As the SynthNV does not reach 6 GHz, a frequency doubler was used to access the 6.8 GHz signal. A power splitter connected to the SynthNV allows for one standard and one frequency doubled output, so both the 3.0 GHz and the 6.8 GHz signal can be accessed from the same device, with the only requirement being to reprogram the SynthNV when switching between Rubidium-85 and Rubidium-87.



Figure 14: Setup of variable microwave source. The Windfreak SynthNV is a variable microwave source that can be programmed to output a given frequency. It can be powered by an external 10 MHz clock. By scanning the frequency of the clock, the frequency of the source can be varied. The microwave signal then goes to a power splitter, with one half of the signal going through a frequency doubler. This setup allows for a 3.0 GHz signal to be output for Rubidium-85 and a 6.8 GHz signal to be output for Rubidium-87 by reprogramming the SynthNV.

6.2 Spin Flips

The sources can be used to evaporatively cool the Rubidium atoms. As a test, we optically pumped Rubidium-87 into the F=1 state and then scanned the SynthNV across the 6.8 GHz resonance. As atoms had their spins flipped to the F=2 state, their signal could be detected using a laser tuned to the right frequency. The results are shown in Fig. 15. There is a clear, wide peak at the resonance. This is a much broader peak than found doing a similar experiment with ⁸⁵Rb (see Fig. 21), possibly due to excessive power broadening. These microwave sources can also be used to sympathetically cool other atoms, such as Potassium, if the atoms are in the same trap. We plan to investigate this in the future.



Figure 15: Atom number vs. microwave frequency for 87 Rb. By scanning the 6.8 GHz source across the Rubidium-87 resonance (indicated by black vertical line) with the atoms in the F=1 state and the imaging tuned to the F=2 state, atoms can be seen as they transition to the F=2 state. Compare to Fig. 21 for the Rubidium-85 data. Data taken by Charles Fancher.

6.3 3.0 GHz Source Amplifier

The output from the SynthNV still needs to be amplified, so we constructed a 3.0 GHz amplifier (see Fig. 16). This amplifier is controlled by the Adwin, the software that runs the apparatus during the cooling and trapping process. The Adwin sends in a TTL signal that controls an on/off switch that can feed the input from the SynthNV into the amplifier, which is powered by a DC power supply. The amplified signal then goes through a circulator to block reflected signals before being output to an antenna that could be put near the vacuum chamber to transmit microwave radiation to the atoms through a quarter-wave antennae.

6.3.1 Circuit Design for Amplifier

The switch that allows the 3.0 GHz signal to reach the amplifier is powered by $\pm 5V$. Because the power supply only supplies $\pm 15V$, a DC/DC converter is needed to create the negative supply. The DC/DC converter also creates a positive power supply, and these supplies have a floating ground. In addition, the TTL signal from the Adwin that controls whether the switch is on or off needs to be isolated from the Adwin to avoid ground loops. This is done



Figure 16: Image of 3.0 GHz amplifier. The 3 GHz microwave source takes an input 3 GHz signal, amplifies it, and outputs it at a power of approximately 33 dBm. A DC power supply powers the amplifier and the DC/DC converter that provides the positive and negative voltages needed to power the switch. The setup is completely controlled by a TTL input from the Adwin, which is optocoupled before being sent to the microwave switch. A circulator stops reflections from passing through the system.

through use of an optocoupler that is grounded to the same ground as the DC/DC converter. All of this is controlled on the circuit board in the box. See Fig. 17 for the circuit diagrams.

6.3.2 Determination of Appropriate Attenuation

The amplifier used for the 3.0 GHz source is, by design, supposed to have a gain somewhere between 33 dBm and 43 dBm, and an output of about 33 dBm, meaning it requires an input signal that is somewhere between -10 and 0 dBm. Too powerful an input signal could result in the amplifier saturating, or developing a flat top on its sine wave. This is equivalent to the amplifier outputting other frequencies, which is not desired. To determine the appropriate amount of attenuation to put into the amplifier, given an output from the SynthNV box of 12 dBm, different attenuations were tested to determine when the amplifier response became nonlinear. The raw results, where the output power was measured with different inputs, are seen in Fig. 18a. The derivative of these results is then shown in Fig. 18b. The slope hovers



Figure 17: Diagram of the circuits on the prototyping board in the 3.0 GHz amplifier box. The DC/DC converter takes the +15V power from the DC power supply and creates a +15V and -15V source with a floating ground. These sources power a +5V regulator and a -5V regulator, which power the switch used to send a microwave signal to the amplifier. The +5V regulator also powers an optocoupler that isolates the TTL signal from the Adwin that is used to turn the switch on and off.

around one before dropping as the amplifier reaches saturation. Thus, an input power of 2 dBm was deemed to be ideal, and so a 10 dB attenuator, corresponding to a power drop of 10 dBm, was add to the 3.0 GHz amplifier box.

6.4 Controlling the External Clock Frequency

We are using an HP 8657B frequency generator to generate the external clock frequency. Although the frequency can be varied manually, it is also possible to modulate the frequency through an external DC signal. This is ideal because then it can be controlled by the Adwin. However, if the external signal is too high, the output response becomes nonlinear as the system saturates. Thus, we tested for the saturation point, and we found that the system began to saturate after 1.8 V (see Fig. 19). Thus, since the Adwin can provide $\pm 10V$, and the internal resistance of the frequency modulator is 593 Ω , a 2700 Ω resistor is added in series to allow for the appropriate voltage to be sent to the clock. Using the 2700 Ω resistor in series and scanning in the negative voltage regime, it was found that the saturation occurred at -10 V (see Fig. 19). Thus the external clock can be scanned to $\pm 1.8V$, or $\pm 10V$ with the



Figure 18: Determining saturation of amplifier. (a) Input power into the 3.0 GHz amplifier versus the measured output power from the amplifier. (b) The ratio between change of output power to change of input power versus the input power. The ratio is calculated based on the change from the previous, lower input power and lower output power. Saturation found to occur at inputs greater than 2dBm.

resistor in series.

6.5 Testing the Antenna

A half-wave dipole antenna was built to be transfer the signal from the amplifier to the atoms. To determine the maximally broadcast frequency range, we measured the amplitude of the signal reflected from the antenna at different frequencies. We scanned from 2500-3600 MHz and plotted the reflected power as a fraction of the output power (see Fig. 20). Less reflected power corresponds to a higher transmitted power and a more efficient broadcast. This antenna has a minimum just below 3 GHz, near the resonance of 3.035 GHz.

7 Magnetometry with Rubidium-85

7.1 Rabi Flopping Theory

When radiation, such as microwave radiation, targets a transition between two energy states, an atom will oscillate back and forth between those two states an a process known as Rabi flopping. In our experiment, Rabi flopping occurs when microwave radiation causes an



Figure 19: Input DC voltage vs output clock frequency. Modulation was set to be 100 kHz/V. Green dots are positive voltage sent into external clock, while blue dots are negative voltage. Negative voltage data was taken with a 2700 Ω resistor in series. Slope was found to be 104 kHz/Volt before saturation, which occurs at ±1.8 V, corresponding to ±10V with a 2700 Ω resistor in series with the clock.

oscillating magnetic field to act on atoms in a static magnetic field. The static magnetic field causes Zeeman splitting of different m_F levels. The perturbative field causes the spins to oscillate between two states at a frequency known as the Rabi frequency. This frequency varies depending on the m_F transition levels, and various other factors. The Rabi frequency Ω_R between states $|F, m_F\rangle$ and $|F', m'_F\rangle$ is given by

$$\Omega_R = \frac{\langle F', m'_F | H_z | F, m_F \rangle}{\hbar} \tag{4}$$

where H_z is the Zeeman perturbation Hamiltonian, given by $H_z = -\mu \cdot \mathbf{B}$. Now $\mu = -\frac{2\mu_B}{\hbar} \mathbf{S}$, where **S** is the spin operator and there is a factor of 2 because g_f for an electron is approximately equal to 2. Then the Rabi frequency, Ω_R , is

$$\Omega_R = \frac{\langle F', m'_F | -\mu \cdot \mathbf{B} | F, m_F \rangle}{\hbar}$$
(5)



Figure 20: Reflected power versus frequency. Reflected power is a fraction of the total output power at that given frequency. Less reflected power corresponds to a higher transmitted power and a more efficient broadcast. This antenna has a minimum just below 3 GHz, near the resonance of 3.035 GHz.

If we say that the constant background field is in the z direction, then we can target two different types of transitions, depending on whether the oscillating field is perpendicular or parallel to the static field. The case where the oscillating field, Bcos(wt), is in the z direction, is known as a π transition. Then the Rabi frequency is

$$\Omega_R = \frac{2\mu_B}{\hbar^2} B\cos(wt) \langle F', m'_F | \hat{S}_z | F, m_F \rangle = \frac{2\mu_B}{\hbar^2} B \langle F', m'_F | \hbar m | F, m_F \rangle \tag{6}$$

where m is the spin being acted upon. In this case, the microwave radiation only targets the electron spin, so in order to do calculations, we must use Clebsch-Gordan coefficients to decompose the F and m_F levels into nuclear and electron spins, and either m = 1/2 or m = -1/2. It is clear that for this transition to be nonzero, due to the orthogonality of the different states, $\Delta m_F = 0$, though we can have $F = \pm 1$.

Now we consider the case when the oscillating field is perpendicular to the quantization

axis, say when the field is in the x direction. We can write $\hat{S}_x = \frac{S_{\pm}+S_{\pm}}{2}$ with $S_{\pm} = S_x \pm iS_y$ and $S_{\pm}|s,m\rangle = \sqrt{s(s+1) - m(m\pm 1)}|s,m\pm 1\rangle$ for some particle of spin state $|s,m\rangle$. If we say that $\mathbf{B} = Bcos(wt)\hat{x}$, then

$$\Omega_R = -\frac{\mu_B^2}{\hbar} B\cos(wt) \langle F', m'_F | S_+ + S_- | F, m_F \rangle \tag{7}$$

Only one operator will act for a given transition, either S_+ or S_- . This leads to a selection rule of $\Delta m_F = \pm 1$, for these σ transitions. Use the Clebsch-Gordan coefficients to decompose the $|F,m_F\rangle$ states into nuclear and electron spin for Rubidium-85 with nuclear spin 5/2 and then solving Eq. 7, we find for instance, that the Rabi frequency $|2,0\rangle$ to $|3,\pm1\rangle$ is $\Omega_R = \frac{1}{\sqrt{3}} \frac{\mu_B B_x}{\hbar}$. In contrast, the π transition from $|2,0\rangle$ to $|3,0\rangle$ is $\Omega_R = -\frac{\mu_B B_z}{\hbar}$.

The rate of transition between states varies as a function of the detuning, δ , where the new Rabi frequency, Ω' is

$$\Omega' = \sqrt{\Omega_R^2 + \delta^2} \tag{8}$$

The probability amplitude of transmission varies due to detuning as $(\frac{\Omega}{\Omega'})^2$ [3], so it is possible to determine the Rabi flopping frequency by scanning the frequency across the resonance and using the formula

$$N_e = \frac{A\Omega^2}{\Omega^2 + \delta^2} \tag{9}$$

where N_e is the number of atoms, and A is an arbitrary constant. This distribution is lorentzian.

7.2 Magnetometry Data

The 3.0 GHz microwave source is useful for evaporative cooling but can also be used for magnetometry because the exact resonance frequency varies due to the changes in energy levels caused by the Zeeman shift. In this experiment we measured the magnetic field inside the MOT cell. First we pumped all of the Rubidium-85 atoms into the F=2 state. Then we scanned the frequency of the microwave source across the resonance and detected atoms in that transitioned to the F=3 state. The complete results are shown with background subtracted in Fig. 21. There are approximately 10 peaks, which correspond to the different energy levels between transition states that satisfy $\Delta m_F = 0,\pm 1$, assuming a linear Zeeman shift (see Fig. 22). This is close to the predicted 11 peaks, but higher resolution data could reveal an additional peak.



Figure 21: Magnetometry with Rubidium 85. Data points taken sweeping the clock 100 Hz over the outer peaks and 10 Hz over the inner peaks, corresponding to approximately 305 kHz and 3.05 kHz, respectively. Background found with microwave off is subtracted. Error bars are standard error.

We took more detailed data of the three central peaks, corresponding to the $|2,0\rangle$ to $|3,0\rangle$ transition, the $|2,0\rangle$ to $|3,1\rangle$ transition, and the $|2,0\rangle$ to $|3,-1\rangle$ transition. Results are shown in Fig. 23. We then fit these peaks to Lorentzian curves and to Gaussian curves (see Fig. 23). Theoretically, assuming no broadening, the fits should be Lorentzian, but with broadening they could be Gaussian, so it was important to see which model fit the data better. The fits, with frequency x, are as follows



Figure 22: Explanation of 11 expected peaks from microwave radiation of Rubidium-85 atoms. Possible transitions are $\Delta m_F = 0, \pm 1$. Red arrows count the 11 peaks. Dashed line shows an example of another possible transition, but this transition is the same energy as the $m_F = 0$ to $m_F = -1$ transition, assuming a linear Zeeman shift.

$$N_e = 0.77e^{\frac{(x-3.0356535GHz)^2}{(12.6kHz)^2}} + 0.44e^{\frac{(x-3.0357315GHz)^2}{(11.4kHz)^2}} + 0.66e^{\frac{(x-3.0358131GHz)^2}{(13.4kHz)^2}} + 0.076$$
(10)

$$N_{e} = \frac{0.91 \cdot (10.1kHz)^{2}}{(10.1kHz)^{2} + (x - 3.035653376GHz)^{2}} + \frac{0.55 \cdot (8.9kHz)^{2}}{(8.9kHz)^{2} + (x - 3.035731825GHz)^{2}} + \frac{0.78 \cdot (11.0kHz)^{2}}{(11.0kHz)^{2} + (x - 3.035813319GHz)^{2}} - 0.02$$
(11)



Figure 23: Magnetometry with Rubidium 85. Closeup of central peak and closest two peaks. Data taken at 10 Hz variations in external clock, corresponding to 3.05 kHz variations in frequency. The three central peaks are fit to a Gaussian and a Lorentzian. Vertical line represents location of zero-field resonance. Error bars are standard error.

Uncertainties of fits are claimed by Matlab fitting program to be within ± 5 on the last digit. The main terms in each the fits correspond to the three peaks, from left to right, while the final term corresponds to a background. The background was supposed to be subtracted, but may not have been completely removed. The Lorentzian, Eq. 11, has $r^2 = 0.981$, while the Gaussian, Eq. 10, has $r^2 = 0.976$. The Lorentzian also has a smaller background term, which is appropriate, and appears by eye to capture the lower and upper parts of the curves better (see Fig. 23). Thus we will assume for the moment that the Lorentzian fit is the accurate one and use it to do magnetometry. We can determine a number of parameters, summarized in Tab. 1.

The Rabi frequency for each transition is the half width at half maximum of the peak, assuming that there is no other broadening. Thus our calculations for this quantity are upper limits. We find that the center peak has a smaller Rabi frequency, $\leq 8.9 \pm 0.5$ kHz than the outer peaks. Using Eq. 6, this suggests an oscillating B field along the quantization axis of approximately $\leq 10 \pm 0.5$ mG, given that $\Omega_R = \mu_B B_z/\hbar$ for this transition. Similarly, the Rabi frequencies for the left and right peak suggest an off-axis B field of approximately $\leq 20 \pm 1$ mG (see Tab. 1). In general, shorter Rabi frequencies lead to narrower peaks

	Left Peak	Center Peak	Right Peak
Corresponding	$ 2,0\rangle \leftrightarrow 3,-1\rangle$	$ 2,0\rangle \leftrightarrow 3,0\rangle$	$ 2,0\rangle \leftrightarrow 3,+1\rangle$
Transitions	$ 2,-1\rangle \leftrightarrow 3,0\rangle$		$ 2,+1\rangle \leftrightarrow 3,0\rangle$
Fitted Frequency (kHz)	$3035653.4{\pm}1$	$3.035731.8 \pm 1$	$3.035813.3 \pm 1$
ΔF (kHz)	78±1	$0.4{\pm}1$	82±1
$B_{DC} ({\rm mG})$	168 ± 10		175 ± 10
FWHM (kHz)	20.2±1	17.8 ± 1	$22.0{\pm}1$
Inferred Ω_R (kHz)	$\lesssim 10.1 \pm 0.5$	$\lesssim 8.9 \pm 0.5$	$\lesssim 11.0 \pm 0.5$
Inferred $B_{ac}\hat{z}$ (mG)		$\lesssim 10 \pm 0.5$	
Inferred $B_{ac}\hat{x},\hat{y} \pmod{\mathbf{G}}$	$\lesssim 20 \pm 1$		$\lesssim 20 \pm 1$

Table 1: Data extracted from Lorentzian fit of the three center peaks. ΔF is frequency shift from known hyperfine transition frequency. The field B_{DC} is the external stray field in the chamber, while B_{AC} is caused by the microwave source. The Rabi frequency is retrieved from the FWHM assuming no broadening, so Ω_R and B_{ac} are upper limits.

and higher resolution, and also allow for faster evaporative cooling because the transitions happen more quickly.

The separation between the central peak and the peaks on the right is 82 ± 1 kHz and the separation between the central peak and the peak on the left is 78 ± 1 kHz. These values are most likely different because the Zeeman splitting is not perfectly linear. We use the approximation of linear Zeeman splitting that the change in energy per change in field for the $m_F = \pm 3$ state is 1.4 MHz/G, and for the $m_F = \pm 1$ state is 1.4/3 MHz/G. Combining magnetic field calculations done with each peaks, we find that the static magnetic field is about 170 ± 10 mG. This value underestimates the error because the splitting is not linear. A similar value is calculated when using the Breit-Rabi formula, which gives the appropriate Zeeman splitting and is not a linear approximation. The field measured is lower than the Earth's field because the trim coils on the apparatus were on and are supposed to shield the apparatus from any stray fields. Given this, the magnetic field is actually much higher than expected. This suggests a way to improve the tuning of the trim coils, which will improve the performance of the molasses and possibly allow for colder atoms.

8 Discussion and Future Experimental Design

We have successfully trapped ⁸⁵Rb atoms in the MOT and magnetic trap. We have also trapped them in small numbers in the dipole trap, though not in the appropriate spin state or in high enough concentrations to form molecules. However, even without molecules, it has been possible to do some magnetometry with Rubidium-85, paving the way for future experiments when the molecules are created. Furthermore, the new microwave manipulation systems that have been built will allow for more atomic spin control, which will enable evaporative cooling and even better magnetometry measurements.

Once we have successfully trapped ⁸⁵Rb atoms in the $|2,-2\rangle$ state and loaded them into the dipole trap at high enough densities, we will try to find the Feshbach resonance at 155 G, which has a width of 11.65 G. As a first attempt for detecting the creation of molecules we will sweep the field from below the resonance to just above the resonance, hold the atoms there for 60-100 ms, and then image the cloud to see if the number of atoms has decreased. We will compare this to images of atoms that have been held at a field above resonance and then moved to a lower field, where supposedly the molecules will have converted back to atoms. This procedure is similar to work that has been previously done on ⁸⁵Rb [5]. From there it will be possible to do more magnetometry and physics with the Feshbach resonance.

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10 Appendix A: Designing the New Dipole Trap

Currently, the Rubidium-87 atoms in the apparatus are first cooled in a Magneto-Optical Trap (MOT) and then moved to a purely magnetic trap. The atoms in this trap are spinpolarized, which is necessary for a Feshbach resonance. From there, the atoms are moved to an optical dipole trap created by a retroreflected 1064 nm laser. Hopefully by instead cooling Rubidium-85 atoms and then sweeping the magnetic field across the Feshbach resonance molecules will be formed. However, Feshbach molecules are formed by atoms colliding, meaning the atoms must reside in a tight, dense trap, ideally tighter than the current dipole trap allows. Furthermore, the current laser is not very stable (frequency and phase-wise). There is another 1064 nm laser in the lab, known as the blue laser, that will be added to intersect the current dipole trap and make a tighter trap. Thus we are going to add the blue laser, which has a much more stable intensity and frequency, making it better able to tightly trap atoms. In fact, it may be good enough to make a Bose Einstein Condensate (BEC). This summer we designed a schematic and ordered the necessary parts to add the blue laser to the apparatus.

10.1 Comparing the Lasers

To make a trap with two different lasers it is important that the wavelength range of the two lasers does not overlap. Otherwise, the lasers could form an optical lattice, which would divide the atoms into multiple groups. To make sure that the wavelengths were distinct, we used the wavemeter to measure the wavelengths of the lasers. The laser already installed, has a peak wavenumber of 9393.82 cm⁻¹ with a full width half maximum of 0.014 cm⁻¹. The blue laser oscillated from about 9395.025 cm⁻¹ to 9395.033 cm⁻¹ with a period of about 6 seconds. Fortunately, there was no overlap in the wavenumber of the two lasers.

10.2 Calculating the Beam Waist

Although the Feshbach molecules we are attempting to create do not begin with atoms in the BEC state, we designed the blue laser setup so that it should be able to make a BEC. In order to be able to create a BEC with the laser that we added, we needed to determine the beam waist of the laser at the focus that would give us the appropriate trap depth. The potential depth of a well with a laser is

$$U = \frac{I}{I_{sat}} \frac{\hbar \gamma^2}{8\delta} \tag{12}$$

where I is the intensity of the beam, I_{sat} is constant equal to 1.6 mW/cm², δ is the frequency of detuning of the laser from the transition frequency of 780 nm for Rubidium, and γ is equal to $2 \cdot \pi \cdot 5.8 \cdot 10^6$ rad/s [3]. For a Gaussian laser beam, the intensity, I, is given as

$$I = \frac{2P}{\pi w_o^2} e^{\frac{-2r^2}{w^2}} (1 + (\frac{z}{z_R})^2)^{\frac{-1}{2}}$$
(13)

where w_o is the width of the beam waist, r is the radial distance from the center of the beam, z is the axial distance from the focus, and z_R is the Rayleigh length given by

$$z_R = \frac{\pi w_o^2}{\lambda} \tag{14}$$

for beam with wavelength λ . Doing a Taylor expansion on Eq. 13 and plugging back into Eq. 12, we find

$$U = \frac{P\hbar\Gamma^2}{\pi w_o^2 I_{sat} 4\delta} \left(1 - \frac{2r^2}{w_o^2} - \frac{z^2}{z_R^2}\right) = C\left(1 - \frac{2r^2}{w_o^2} - \frac{z^2}{z_R^2}\right)$$
(15)

Then the frequency of oscillations in the radial direction is found to be

$$\omega_r^2 = \frac{4C}{mw_o^2} \tag{16}$$

and the oscillation frequency in the z direction is similarly

$$\omega_z = \sqrt{\frac{2C}{m^2 R^2}} \tag{17}$$

Finally, the mean oscillation frequency is

$$\bar{\omega} = (w_r^2 w_z)^{\frac{1}{3}} = \frac{P^{\frac{1}{2}} \hbar^{\frac{1}{2}} \gamma \lambda^{\frac{1}{3}}}{2^{\frac{1}{6}} \Pi^{\frac{5}{6}} w_o^{\frac{7}{3}} I_{sat}^{\frac{1}{2}} \delta^{\frac{1}{2}} m^{\frac{1}{2}}}$$
(18)

The Schrodinger's equation for a Bose Einstein Condensate takes the form

$$\left(\frac{-\hbar^2 \nabla^2}{2m} + U_{ext}(\vec{r}) + g |\Phi(\vec{r})|^2\right) \Phi(\vec{r}) = \mu \Phi(\vec{r})$$
(19)

where $U_{ext}(\vec{r})$ is the trapping potential and $g|\Phi(\vec{r})|^2$ is the interaction between the particles, which are all assumed to have the same wave function, with g defined as

$$g = \frac{4\pi\hbar^2 a}{m} \tag{20}$$

with scattering length a and mass m. If the atoms react repulsively, which is true in the case of ${}^{87}Rb$, then the condensate density is essentially that of a parabola in a well if the Thomas-Fermi approximation is used [4]. The chemical potential energy of the atoms in the well is defined as

$$\mu = \frac{\hbar\bar{\omega}}{2} \left(\frac{15Na}{a_{ho}}\right)^{\frac{2}{5}} \tag{21}$$

where $a_{ho} = \sqrt{\frac{\hbar}{m\bar{\omega}}}$ is the length of a harmonic oscillator.

We measure the temperature of the atoms in the trap by releasing them then imaging the expansion of the cloud of as they fall. When they are released from the trap all of the chemical potential energy is converted into kinetic energy as the outer atoms in the cloud move at a speed of v_{ρ} , which for our apparatus and our imaging system needs to be about 1 cm/s. By setting the kinetic and potential energy equal to each other, we find that $\bar{\omega}$ is



Figure 24: Planned setup of beam path for new laser. Waveplate below beam splitter cube allows beam to be reflected or transmitted by cube, depending on where in the apparatus the beam will be sent. Beam then passes through 2:1 telescope and then is focused through a 30 cm focal length lens before being sent into the MOT.

$$\bar{\omega} = \frac{m^{\frac{2}{3}} v_{\rho}^{\frac{5}{3}}}{(15Na\hbar^2)^{\frac{1}{3}}} \tag{22}$$

By equating Eq. 22 with Eq. 18, and solving for the beam width w_o , we find

$$w_o = \frac{15Na\hbar^{\frac{7}{2}}P^{\frac{3}{2}}\gamma^3\lambda}{\sqrt{2}\Pi^{\frac{5}{2}}I^{\frac{3}{2}}_{sat}\delta^{\frac{3}{2}}m^{\frac{7}{2}}v_o^5}$$
(23)

Setting the scattering length to $100a_o$ and the number of atoms, N, to 3×10^4 moles, the power to 1W, and calculate for ${}^{87}Rb$, the necessary beam width is 17.5 μ m. This gives us oscillation frequencies of $\omega_r = 2\pi \times 1.5$ kHz and $\omega_r = 2\pi \times 20$ Hz.

10.3 Designing Trap and Ordering Materials

Since the beam waist has to be 17.5 μ m, the beam is about 2.8 mm on the platform, and we will use a 30 cm focal length lens to focus the beam, we want a 2:1 telescope to expand the beam before the focusing lens assuming a Gaussian beam shape. To reduce spherical aberrations, we ordered a 30 cm focal length achromatic doublet to focus the beam and -10 cm and a 20 cm focal length achromatic doublets for the telescope. Thus we are able to design the setup to put the new laser into the trap. We will use a waveplate and beam splitter cube to send the beam into the MOT when desired. The setup is shown in Fig. 24.

11 Appendix B: Microwave Device Procedures

11.1 SynthNV Directions

Standard use:

- 1. Plug in output.
- 2. Plug in external clock.
- 3. Plug in power supply.

Changing frequency coarsely:

- 1. Plug in external clock.
- 2. Plug USB cable into computer with SynthNV software installed.
- 3. Open SynthNV software.
- 4. Change frequency using large knob and the appropriate step-sizes (generally 3.4 GHz for 87Rb and 3.05 GHz for 85Rb.
- 5. Under Extras tab, press Eeprom and wait for green light to turn on and off.
- 6. Close program and turn off device.

DC Frequency Modulation with Frequency Generator:

- 1. Place 2700 Ω resistor in series with external modulation input.
- 2. Turn on DC FM (press shift, then DCFM).
- 3. Increase DC FM to desired kHz/V modulation, given that the frequency generator saturates at ± 1.8 V, which corresponds to ± 10 V on the Adwin.

11.2 3.0 GHz Amplifier Directions

- 1. Turn on main power switch.
- 2. Turn on 3.0 GHz input source (now or anytime after the first step).
- 3. Turn on switch to send TTL signal to amplifier.
- 4. Put in TTL Adwin signal when ready.

12 Appendix C: Feshbach Energy Dependence

In addition to the creation of Feshbach molecules, finding a Feshbach resonance will allow for the study of some of the properties of the Feshbach resonance. In particular, the location of the Feshbach resonance is predicted to vary with the energy of the colliding atoms [7]. The effective scattering length, a_{eff} , has been calculated to be, compared to the background scattering length a_{bg} ,

$$a_{eff} = a_{bg} \left(1 - \frac{\Delta B \left(1 + \frac{E}{E_b}\right)}{B - \left(B_0 + \frac{E}{E'_m} - \Delta B \frac{E}{E_b}\right)}\right)$$
(24)

where B is the magnetic field, E is the kinetic energy, E_b is the binding energy for the background scattering length, and E'_m is the derivative of the magnetic energy with respect to the magnetic field [7]. This formula shows that as the kinetic energy of the atoms changes, the scattering length and thus the location of the divergence of the scattering length, or the location of the Feshbach resonance, can change.

One possible way to test the energy dependence of the Feshbach resonance is to give the atoms some kinetic energy, by dividing the atoms into two traps and then letting the atoms fall together. This can be done by placing them in an optical dipole trap and then creating two traps using an additional laser which is detuned from resonance in the opposite direction, making a barrier instead of a trap. The potential depth of a well with a laser, or height of a barrier, is

$$U = \frac{I}{I_{sat}} \frac{\hbar \gamma^2}{8\delta} \tag{25}$$

where I is the intensity of the beam, I_{sat} is constant equal to 1.6 mW/cm², δ is the frequency of detuning of the laser from the transition frequency of 780 nm for Rubidium, and $\gamma = 2\pi \times 5.8$ MHz [3]. Now we approximate the trap as a parabola and find the potential, U_T , along the direction of propagation of the beam is

$$U_T = \frac{P_T \hbar \Gamma^2}{\pi w_o^2 I_{sat} 4\delta} (1 - \frac{z^2}{z_R^2}) = C(1 - \frac{z^2}{z_R^2})$$
(26)

where P_T is the power of the laser and w_o is the beam width at its smallest point. Now without using the Taylor approximation and looking at the radial direction of the beam we find that the potential of the barrier, U_B is given by

$$U_B = \frac{P_B \hbar \Gamma^2}{\pi w_o^2 I_{sat} 4\delta} e^{\frac{-2r^2}{w^2}}$$
(27)

We want the difference between the potentials of the two traps formed with the barrier and the original trap to equal a kinetic energy large enough to cause a shift in the location of the Feshbach resonance, which corresponds to a speed of about 4 - 7 cm or an energy of about 0.5-1 MHz. Given that the trap beam is approximately 1 W with a 1064 nm beam, and the barrier will be produced with a 770 nm laser with a beam width of 2.5 mm, and looking for a kinetic energy of 1 MHz, we can solve for the power of the barrier laser.

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