Investigation of Laser Cooled Atoms

Honors Thesis

Presented to the Center for Interdisciplinary and Special Studies

Of

The College of the Holy Cross

By

Kendy Hall

Thesis Advisor: Timothy Roach

Reader: Janine Shertzer

May 2, 2002

Table of Contents

Chapter 1: Introduction

Chapter 2: Apparatus

Chapter 3: Laser Cooling

Chapter 4: Rubidium and Lock-In Amplification

Chapter 5: Measuring the Temperature of Cold Atoms

Acknowledgments

There are a couple of individuals that I would like to thank for their support and assistance:

My family, especially my parents, Sidney and Diane Hall, for their tender love, care, and support throughout my Holy Cross education, and for understanding that I really wanted to be in Memphis over the past two summers, but instead I had to spend those summers here in Worcester.

Special thanks to my cousins, Travis Flowers and LaMarcus Malone, for giving me motivation during the many difficult times when I was extremely stressed and wanted to quit.

My research advisor, Timothy Roach. First, for giving me the opportunity to do research in his lab, and not yelling at me when I destroyed things. Second for his support as I wrote my thesis. Lastly, for teaching me that patience is really a virtue because he needed it in assisting me.

My reader, Janine Shertzer, for assisting in the writing process of my thesis, and for her motherly assistance in helping me decide on a graduate school.

De-Ping Yang, for helping me prepare my thesis presentation. At the time, I was extremely upset with him because he made me change my slides so much, but it all work out for the best. Also thanks for so many other things that you helped me with.

Holy Cross Physics Department
To all the professors: I would mention each professor by name, but that would get rather lengthy. Thanks so much for the things you have taught me, and especially for the guidance that you have given me. In some way each one of you have taught me valuable lessons that I will keep with me forever.

Lastly, I want to dedicate my thesis to my Grandmother who passed away this Spring. Thank you so much for all the things that you have shown me in life. I love you and think about you everyday. Remembering your lovely smile will always bring joy to my heart. I will forever miss you.

Motivation

When asked to join the honors program my sophomore year, the title of my essay was “Opportunity of a Life Time.” Working with Dr. Timothy Roach has been the greatest joy that I can ever imagine. These last two years I have truly been every bit of the opportunity that I spoke experiencing in that essay.

Ever since I can remember my first desire to learn physics, I have been intrigued by Albert Einstein. I chose this topic for my thesis because just recently one of Einstein’s predictions has been proven in the laboratory: Bose-Einstein Condensation, using laser cooling and trapping technology. The ability to investigate this phenomenon gives me great joy and has been the driven force behind my research.

I began helping prepare the new lab for atomic research using laser cooled atoms the summer after my sophomore year and continued the summer following my junior year. During those two summers, I completed several projects and experiments that resulted in my understanding of this relatively new phenomenon. Based on my summer experiences, I decided to continue to work with the research group my senior year, and chose atomic cooling as my honors thesis topic.

Chapter 1

Introduction

1.1 Quantum Theory

In quantum mechanics, under certain conditions electromagnetic radiation can exhibit “particle” characteristics, and matter can exhibit wave properties. In order to study these wave properties, the matter must have a large De Broglie wavelength, $\lambda = \frac{h}{mv}$, where m is the mass of the object, v is the velocity, and $h = 6.626 \times 10^{-34} J \cdot S$ is Planck’s constant. One way to this wave phenomena is to scatter the atoms off a known potential and to look for interference effects. For small particles such as electrons, where $m = 9.11 \times 10^{-31} kg$, their wavelength is approximately $10^{-10} m$ at room temperature. But for larger particles, such as atoms, in order to get a comparable wavelength their velocity has to be very small. Maxwell’s gas law tells us that the average kinetic energy is proportional to the temperature. By cooling the atoms, we lower the velocity. It is at these low temperatures that the De Broglie wavelength is long enough to study the wave properties. Cooling atoms to these temperature is done using lasers and magnetic coils to create a magneto optic trap (MOT).

1.2 Brief History of Laser Cooled Atoms

Within the last half of the 20th Century, major strides have been made within laser technology, which has improved physicists' ability to manipulate and trap atoms in a confined space inside an evacuated chamber. Laser-cooling of atoms is one of the expanding topics in physics, and Atomic, Molecular, and Optical (AMO) physics has emerged as one of the most fascinating areas in physics due to these advancements in lasers. In 1997 the Nobel Prize in Physics was given for advancing the technology of cooled and trapped atoms, and more recently, in 2001, for Bose-Einstein condensation, which is an exotic quantum state of a cloud of extremely cold atoms.

1.3 Research Group

The overall goal of our experiment is to specifically demonstrate the action of slow atoms under the influence of laser light and a magnetic field, and the reflection of these slow atoms off a magnetic surface. Laser cooling involves the process of using a laser to slow the motion of a gas of atoms so that their temperature is near absolute zero, as low as 1 micro Kelvin. Atom trapping is the ability to hold the cooled atoms, in our case using a combination of laser light and a magnetic field called a magneto optic trap (MOT).

Our research group is interested in cold atoms because one can demonstrate the wave nature using the phenomenon of diffraction. Diffraction laws state that a wave that scatters off a finely stripped reflective surface will reappear at certain discrete angles. In previous work, laser cooled rubidium atoms were dropped onto a striped magnetic surface. As they fell they gained downward momentum, but then were repelled by the strong magnetic field of the surface, causing them to bounce back up. This reflection was observed, but the large gain in momentum (and reduction of wavelength) prevented measuring any wave characteristics in the distribution of reflected atoms.

We are in the process of extending the previous research that demonstrated the scattering of laser-cooled Rb atoms off a striped magnetic surface. We are now using a more finely striped magnetic surface and using laser light forces to throw the atoms upward where they will strike the magnetic surface near the top of their trajectory. In this way, their average momentum will be near zero, primarily determined by their temperature. The temperature of the atoms is important for the same reason as mentioned earlier: we want the cloud of atoms to have small momentum and thus a large wavelength, so they will scatter off the surface at large angles. In the previous experiment the gain in momentum as the atoms fell caused the atoms to scatter at small angles and prevented any demonstration of the wave characteristics of the slow atoms.

1.4 Thesis Outline

The major goal of my research thesis is to assist in producing the cooled atoms and measuring and analyzing the temperature of the cloud of atoms using a Time-of-Flight (TOF) technique. This technique determines the velocity by observation of the expansion of a cloud of cold atoms once they are released from a trap. In order to produce cold atoms, one must first understand how to properly use laser technology and precision techniques in order to tune and stabilize a laser to the exact frequency at which the atoms are excited. Therefore my thesis will include explanations and descriptions of some of the precision techniques and the experimental apparatus that I constructed in the lab.

First, I constructed an external cavity diode-laser system. In doing so, I learned how to successfully control a diode laser and how to adjust the optical parameters in order to tune the laser to the proper frequency for cooling and trapping Rb atoms. Second, I became familiar with high vacuum technology, such as the turbomolecular pump, ion pump, and high vacuum gauges. I also identified and calibrated spectra of rubidium for use as frequency locking references. Lastly, I completed and tested the electric control systems of the laser and built a feedback circuit to frequency lock the diode laser.

Chapter 1 begins with a description of our laser and the devices we use to operate and stabilize the laser. I will also introduce other instruments and devices we use in the experiment. Chapter 2 discusses the theory of how lasers work. I will also discuss the Magneto Optic Trap (MOT). In Chapter 3, I will discuss the technique we use to keep the laser locked at 780nm, spending most of the chapter discussing the significance of the Doppler-free saturation absorption spectroscopy experiment, and explaining the atomic structure of rubidium and why we are cooling rubidium atoms instead of a different element. Chapter 4 describes some different mathematical models of the Time of Flight technique we will use to measure the temperature of the cloud of atoms. I will conclude with a brief overview of the importance of my research to the future of the research group.

Chapter 2

Apparatus

2.1 The Diode-Laser

Our laser is a Hitachi (HL78516) 785 nanometer (nm) near infrared laser, with a threshold current of 45 milliamperes (mA) and a maximum operation current of 170mA. We operate the laser at 60mA. We do not operate our laser at more than 80mA because we will be using a grating to reflect part of the laser directly back into the laser. If the intensity of the beam that travels back into the laser has too much high the laser itself can be destroyed.

2.2 Laser Precision Devices Overview

The diode laser is a very sensitive device. For a laser to operate properly, one must be able to control and monitor the temperature of the laser for reasons that I will discuss in this chapter. The current must also be stable. Controlling the current and the temperature of the laser gives us precise control over the frequency of the laser. A grating that reflects a percentage of the light back into the laser gives further control. To ultimately stabilize the laser we will measure the laser absorption in a cell of Rb gas, which allows us to set the frequency of the laser and lock it at that frequency using electrical feedback. I will discuss this technique in detail in Chapter 2. Figure 2-1 is a diagram of our laser.

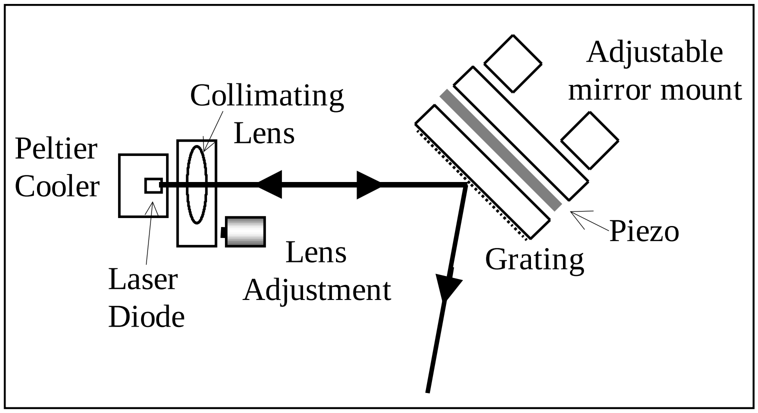


Figure 2-1 Diagram of an external cavity diode laser
[Roach, 1995]

2.3 Laser Temperature Control

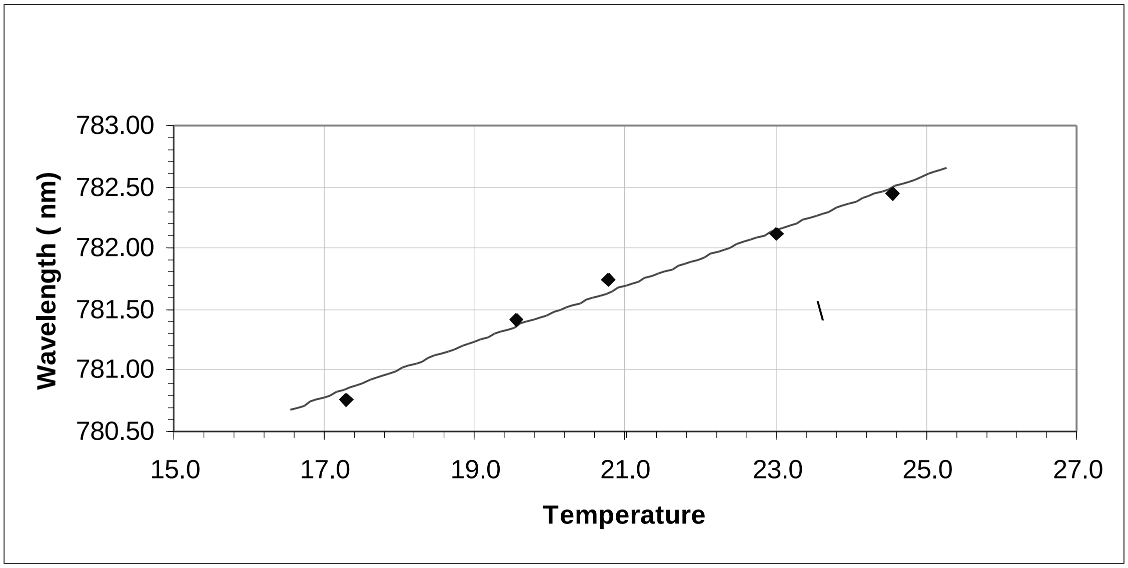


Figure 2-2: Wavelength vs. Temperature

Control of the temperature is extremely vital to the operation of a laser because any small change in temperature affects the wavelength of a laser. You can see from Figure 2-2 that as the temperature of the laser increases the wavelength becomes larger. A heating and cooling unit specifically for the lab controls the temperature of the room. We control the actual temperature of the laser using a thermoelectric module.

2.4 Thermoelectric Module (Peltier Cooler)

The thermoelectric module (Peltier Cooler) allows us to adjust and fix the temperature of the laser. Figure 2-1 shows a drawing of the thermoelectric module attachment to the laser. The device is fixed between two aluminum plates and the aluminum plates are glued to the bottom of laser mount. The aluminum plates allow the device to smoothly distribute the heat from the thermoelectric module to the laser. The thermoelectric module has two sides to it. On one side, the device heats as current flows positively, and on the other side, it cools as current flows positively. Reverse current does not destroy the device; it only switches the job of the two sides. Figure 2-3 is a plot that shows the effect of positive and negative flowing current through the thermoelectric device. Side A is when the cooling temperature is being measured using positive current, and side B is when the cooling temperature is measured using negative current.

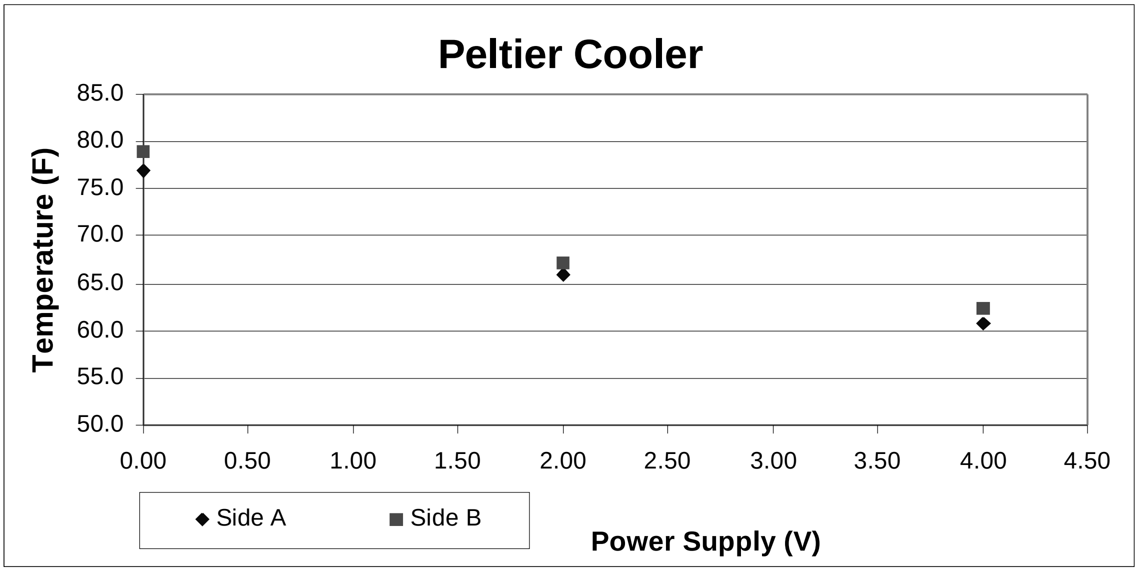


Figure 2-3: Peltier Cooler Performance

The thermoelectric module appears to reduce the temperature of the laser from room temperature down to about 60 degrees Fahrenheit, which correspond to adding about 5 Volts to the thermoelectric module. After the voltage is turned up further than 5 Volts, the temperature becomes unstable because the hot side of the thermoelectric module gets so hot that it causes the cold side to rise instead of drop in temperature. Although the device has limitations, it works perfectly well for our experiment.

2.5 Laser Diode Driver

To control the current of the laser a home-built laser diode driver is used, built around a commercial module (LDD 2P by Wavelength Electronics). The laser diode driver allows us to adjust the laser and to set a current limit to protect the laser by preventing any high current from passing through the laser. Also for further protection of the laser, the driver slowly turns on the current so that a sharp high current does not suddenly travel into the laser, which could destroy it. The current limit and actual current are monitored via a signal in volts instead of current with the relationship being:

$$V_{pin} = I_{\lim it/current} \times \frac{2.5V}{200mA} \qquad (1)$$

Like the temperature, a change in current also shifts the laser's wavelength. This is shown in Figure 2-4.

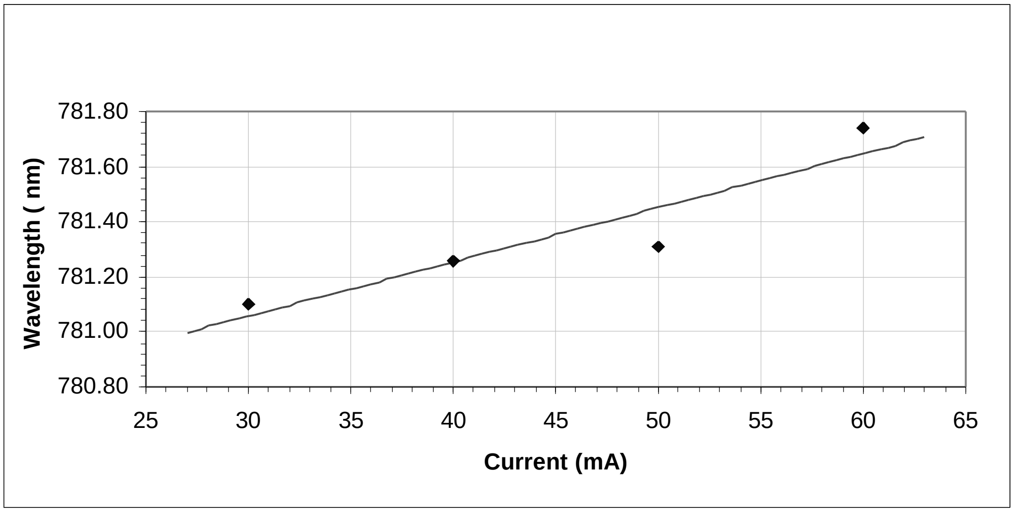


Figure 2-4: Wavelength vs. Current

2.6 Grating

The laser beam is set up to hit an optical diffraction grating so that two beams will reflect at different angles, as seen in figure 4. The grating is oriented so 65.7% of the beam travels back into the laser, and 13.7% is used for our experiment. Because the laser diode is extremely sensitive, we limit the operational current to 80mA so that intensity of light that reflects back into the laser does not damage the laser.

Once the beam reflects back into the laser, the path the beam travels in a round-trip becomes longer than initially. The length of cavity that the beam travels through is important because it determines the wavelength of the modes of the laser. The wavelength therefore shifts as the cavity is lengthened or contracted.

2.7 Piezoelectric Stack

Also seen in Figure 2-1 is a small piezoelectric stack (piezo) (model AE0203D04 by Thorlabs) that is attached to the grating. This device controls the length of the cavity of the laser under the influence of an applied voltage, up to a maximum voltage of 150V. By using an external device to sweep the voltage, we can scan a particular range of laser frequencies. Once the desired frequency is found, we can manually set the piezoelectric stack to a certain voltage so that we can remain at that frequency. We are also able to send an oscillating voltage into the piezo driver in order to modulate the laser for spectroscopy purposes. By sweeping through the frequencies of the laser, we see the spectral lines of the gas of rubidium atoms and we can use this spectrum to lock the laser at a particular line. Chapter 3 will discuss this process more thoroughly.

The piezoelectric stack only becomes effective when the grating is aligned so that the reflecting beam travels directly back into the laser. There are a number of ways to properly align the grating and each technique requires a bit of practice. I will outline the process of the technique that requires the least amount of time. In order to perform this technique you must have an IR video camera.

1. Align the grating so that the reflecting beam travels back into the laser as good as your eyes allow you to.

2. Point the camera and laser onto an index card or a black sheet of construction paper. Turn the lights off (depends on the lighting in the lab, but for first timers this is a good idea)

3. Turn the laser down just below the threshold current. That is when the laser begins to start lasing. You should easily be able to see this using an IR camera.

4. Adjust the grating adjustment knobs until you see a sharp increase in laser intensity, observed with the IR camera.

2.8 Other Instruments and Devices

Figure 2-4 is a diagram of our optical table. I will briefly describe each device’s function. I will discuss the most important instruments and devices in the following chapters.

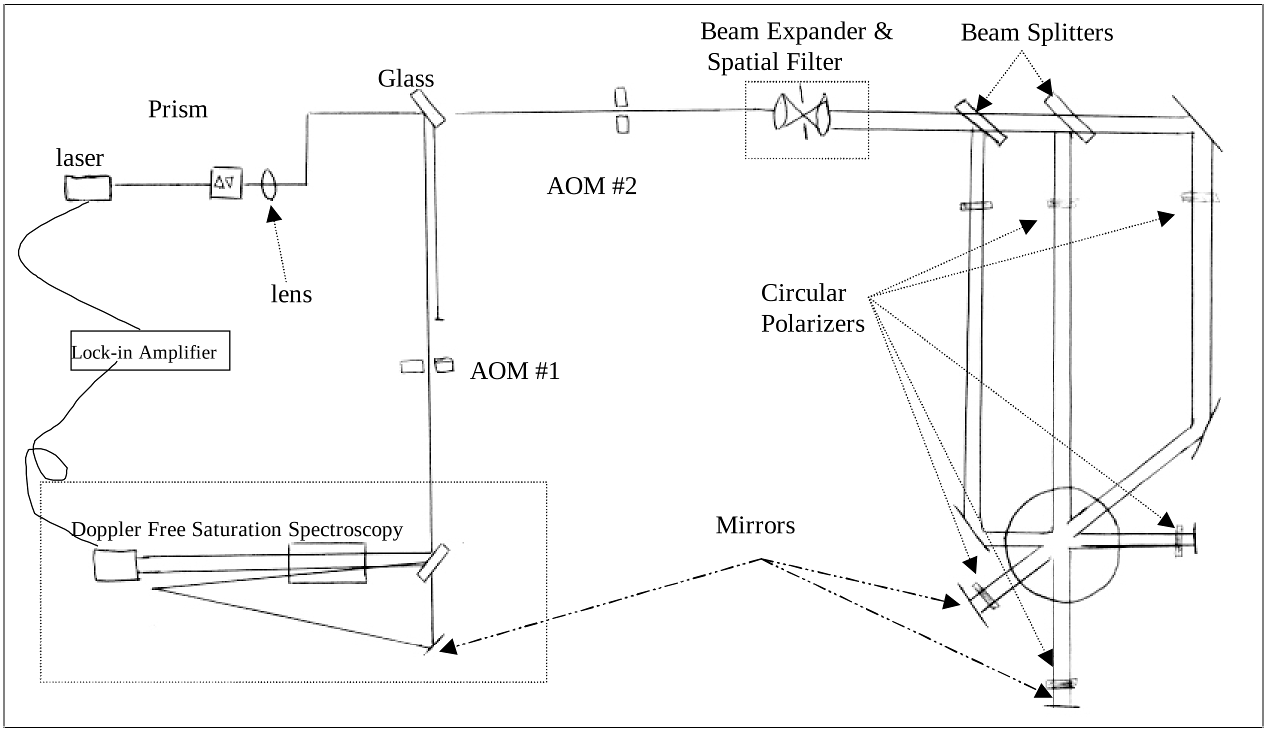


Figure 2-4: Optical Table

- Laser: Not shown here or in the laser in Figure 2-1 is the microwave frequency that we input into the laser to add extra pumping (see chapter 4).

- Prism: The anamorphic prism changes the original beam shape from an oval to a circle.

- Lens: The lens has a focal length of 750 mm and is use to decrease the beam size so that it will fit through both AOM's.

- AOM's: AOM is an acronym for Acousto Optic Modulator. They are use to shift the frequency of the light by 60-100 MHz.

- Glass: The two thick glass plates are use to split the light into three beams as shown in the diagram. The two reflected parallel beams are approximately 4% of the original light, and beam that passes directly through is approximately 92%.

- Polarizers: The six polarizers are used to circularly polarize the light (see chapter 3).
- Filter: Makes the circular shape of the beam smoother.
- Expander: Expands the beam to a diameter of approximately 1 cm.
- Splitters: Splits the laser into 3 beam with equal Intensities.
- Spectroscopy: Doppler Free Spectroscopy setup which is used to obtain the hyperfine spectrum of rubidium which we use to lock the laser.
- Lock-in: Stabilizes the laser through a feedback process (see Chapter 4).
- Chamber: Evacuated chamber where we cool the atoms. The pressure inside is approximately $3\times10^{-9}\,mbar$.

Chapter 3

Laser Cooling

3.1 How does a Laser Work?

First, let’s briefly review the structure of an atom using Bohr’s theory [Ohanian, 1995]. An atom is made up electrons, protons, and neutrons. The protons and neutrons are tightly bound together by the nuclear force and form the nucleus of an atom. The electrons travel around the nucleus in distinct orbits. You can think of the orbits also as levels with distinct energies. In a neutral atom, the number of protons always equals the number of electrons. An electron always wants to be in the lowest possible energy level and will eventually fall down to that level; this process is called spontaneous emission. As the electron drops to a lower level it emits a photon with a frequency that is given by the following equation: $v = \frac{\Delta E}{h}$, where ΔE is the difference of the two levels, and h is Planck’s constant.

Early in the twentieth century, physicists understood that electrons could absorb energy and be excited up to a higher energy level. Einstein came along and showed that you can also force an electron to fall into a lower level if you hit it with a photon with the right amount of energy. As the electron falls, a photon is emitted, just as in spontaneous emission, so the process is called stimulated emission. The emitted photon and the incident electron are in phase because they are identical to one another. Einstein also showed that the probability of photon absorption by an atom in the lower level is equal to the probability of stimulated emission by an atom in the upper level [Griffiths, 1994].

In stimulated emission, a photon that knocks an electron down to a lower level can cause a chain reaction, and the concept of light amplification automatically follows because two photons emerge, the incident photon and the emitted photon. The chain reaction is started because those two photons cause two more photons to be emitted for a total of four, and those four photons cause four more to be emitted totaling eight, and so on. All the photons emitted are identical meaning that they have the same wavelength and frequency making the light monochromatic. In order to create amplification there must be more electrons in the higher level than in the lower level otherwise atoms in the lower level will absorb the photons. This means that the electrons in the lower level must first be pumped up to a higher level. This arrangement is called a population inversion. Creating a population inversion that is continuous is the basic principle behind the operation of the LASER, which means the Light Amplification by Stimulated Emission of Radiation. Without a continuous population inversion, a laser can not work.

Einstein’s theory on the probability and rate of emission or absorption being equal also tells us that we could never get photon amplification if we tried to optically excite electrons in a two level atomic system because at best only one-half the electrons will eventually end up in the upper state [Griffiths, 1994]. To overcome this dilemma, processes involving three or four levels are used. Both operate in similar ways. First you to force most of the electrons that are in the ground level up to an unstable level in which the electrons will fall to a metastable level that is higher than the ground level. Metastable means that the probability for spontaneous emission is very low. This is where the population inversion occurs because as all the electrons will eventually end up in this higher metastable level. Now once an electron falls down to the ground or other lower level, the amplification process as mentioned above begins. The pumping is maintained continuously to produce a beam of light. Mirrors are often used to reflect the photons so that they will make multiple passes through the atoms and so help stimulate more photon emissions [Griffiths, 1994].

The process that I just described is the basic theory behind a gas laser. Our laser is a semiconductor diode, and it operates in slightly different way. To be very brief, a diode is made of two types of materials, p- and n-type, with different electrical properties. Each material has two upper energy bands, the top of one being the conduction band and the lower the valence band. In the n-type material, the valence band is completely full of electrons, and the conduction band is mostly empty so that the electrons in it can flow freely. In the p-type material, the valence band is not completely full of electrons, and there are no electron in the conduction band.

Once the two materials come together, the electrons in the conduction band are above the empty spaces in the valence band, which are known as holes. This creates a population inversion. A current is applied to the diode which adds electrons to the conduction band in the n-type and depletes the electrons in the valence band of the p-type. This continuous flow of current through both materials creates a laser.

3.2 How do Lasers Cool Atoms?

A laser beam cools a gas of atoms by decelerating them. The beam of monochromatic light contains photons with momentum, $p = \frac{h}{l}$. As the laser beam comes into contact with an oppositely moving atom, if the laser beam is at the resonance frequency of the atom, it causes the atom to emit or absorb a photon. Once the atom absorbs a photon, it will receive a boost of momentum and begin to decelerate as the atom travels into the laser beam. The deceleration is due to conservation of momentum. The force is proportional to number of photons that the atom scatters per second [Chu, 1992]. The photon scattering rate for a single laser beam is

$$\Gamma_{sc} = \left(\frac{I / I_s}{1 + I / I_s + (2\Delta / g)} \right) \frac{g}{2} \tag{1}$$

where the resonance natural width $g = \frac{1}{t}$, is the inverse of the natural lifetime, I is the light intensity, and I_s is the saturation intensity of the transition. $\Delta = (w_A - w_L - w_D)$ is the de-tuning between the light (frequency w_L) and the atomic resonance (frequency w_A) taking into account the Doppler shift w_D [Roach, Chapter 4].

Atoms in a gas move in all directions, some towards and some away from the laser beam. So, to increase our chances of cooling the atoms, we use two counter-propagating beams that are tuned a little lower than the resonance frequency. Some atoms will be moving at just the right velocity so that the light from one of the laser beams appears at the resonance frequency due to the shift created by the atoms motion. They rapidly absorb photons and slow down due to the photon scattering force mentioned above. For atoms moving away from the light, they will experience an opposite Doppler shift, and will not absorb photons as strongly as the atoms moving into the light because they will be moving away from the resonance frequency. These atoms will experience a scattering force that will increase their speed, but the force is extremely small compared to the force of on atoms moving into the laser beam [Cohen-Tannoudji and Phillips, 1990]. The overall net force of the two beams will eventually slow down the atoms along the direction of the two laser beams. If you use six counter-propagating beams along three perpendicular axes, you will slow down the atoms in all directions.

There will be fast atoms that will collide with the atoms that are being slowed, but the slowing forces created by the six counter-propagating beams are strong enough to overcome the random impulses of the colliding atoms, thus the cooled atoms are said to be in a “optical molasses”. The atoms will eventually reach a low average velocity and cool no further because the frequency of the cooled atoms are slightly somewhat away from the laser frequency because there is almost no Doppler shift [Phillips an Metcalf, 1987].

As an atom absorbs a photon, it will also de-excite and emit a photon in random direction by spontaneous emission in order to conserve energy which also heats up the atoms. Although the momentum kick is very small, it is not exactly zero, so the heating force competes with the cooling force mentioned earlier and causing a cooling limit. This Doppler limit is given by the following equation:

$$T_D = \frac{\hbar\gamma}{2k_B} \quad (2)$$

$\gamma = \frac{1}{\tau}$, and for rubidium $\tau = 25\,\mathrm{nsec}$, therefore $T_D = 150\,\mu K$.

By choosing certain polarizations of light, one can cause shifts in the magnetic sublevels of the ground state to achieve lower temperatures. This process is rather complicated and I will not describe it [Roach, Chapter 4].

I will note that we use circularly polarized light which allows us to cool to temperatures as low as a few micro-Kelvin.

3.3 Magnetic Field

The atoms mentioned above are cooled using two velocity dependent forces. The first is the laser light itself using the Doppler shift phenomenon. Then circularly polarized light is used to cool the atoms further. In order to confine the atoms, we introduce a magnetic quadrupole field that creates a position dependence to go along with the two velocity dependencies. The magnetic field becomes greater as the atoms move away from the center of the trap where the six counter-propagating beams meet. The magnetic field creates a varying change in the energy levels of the atoms which causes them to absorb more light as their resonance frequency shifts towards the laser frequency. The magnetic field is such that the atoms become more resonant with the laser beams as they travel away from center of the trap. [Roach, Chapter 4] So as they travel away from the center the field and lasers create a restoring force which pushes the atoms back toward the center of the trap.

By combining the three techniques: six de-tuned counter-propagating beams, polarized light, and magnetic fields, we are able to cool atoms to temperatures as low as a few micro-Kelvin and confine them a small region creating a Magneto Optic Trap (MOT).

3.4 References

There are other techniques that you can use to trap atoms, but the process describe in this chapter is the way our trap works. The references for this chapter have more theoretical descriptions to the process of laser cooling and briefly mention the different ways you can trap neutral atoms.

Chapter 4

Rubidium and Lock-in Amplification

4.1 Why do we use Rubidium?

The most commonly used neutral atoms in atomic cooling experiments are those from column one of the periodic table. All of these atoms have just one outer valence electron. For this single electron, the Coulomb binding force is weak compared to that holding the electrons in the inner orbits. Only this single electron is involved in most chemical and optical processes for these atoms.

Although it is theoretically possible to excite the electrons of other elements in order to do laser cooling, the column one elements have an advantage because there are fewer allowed energy levels. If there are more levels, then one needs more frequencies of light in order to control the electronic transitions. For example rubidium has 2 low level states and we only need two colors of light.

The cooling process mentioned in the previous chapter theoretically works for any of the column one elements. Rubidium is a column one element, and we use it in our experiment. Two important reasons we have chosen rubidium atoms following. First, there are readily available inexpensive tunable diode lasers that operate at the wavelength that corresponds to the energy of the rubidium cooling transition. Secondly, a low pressure gas of Rb can easily be produced by evaporation of the metal or from a commercially available “getter” source.

4.2 Atomic Structure of Rubidium

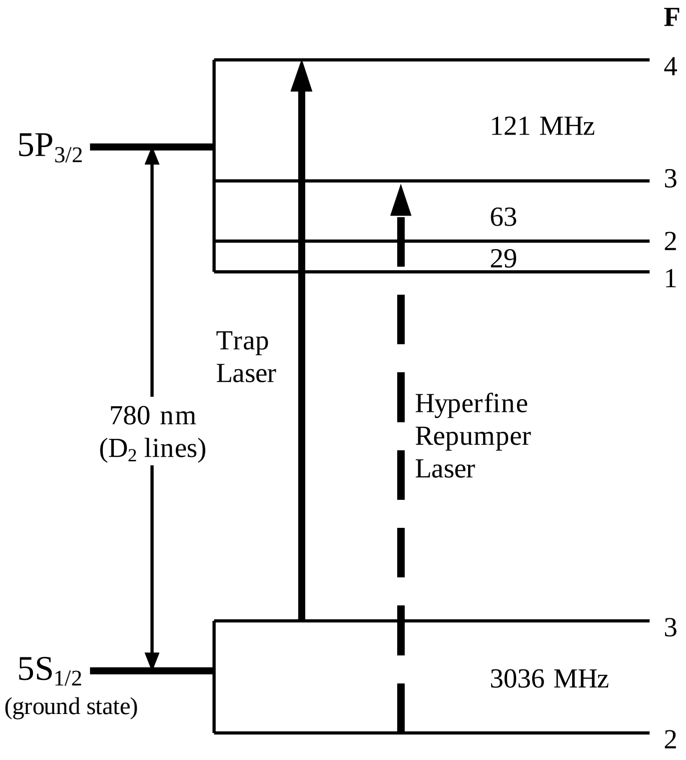


Figure 4-1 Energy Levels of Rb 85

Pure Rubidium has two isotopes, ^{87}Rb and ^{85}Rb, with a natural abundance of 28% and 76% respectively. The ground electron configuration of Rb is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s^1$. For our laser cooling we are exciting the atoms from $5s_{1/2}$

level up to the $5p_{3/2}$ level. Figure 4-1 shows the atomic energy levels of ^{85}Rb. As you see in the figure the energy gap between the two levels corresponds to a wavelength of 780nm. The splitting of the two levels are due to the spin-orbit coupling. The F quantum numbers are used to label the levels split by the hyperfine interaction. $F = I + L + S$, where I is the nuclear spin, L is the electron orbital angular momentum, and S is electronic spin. As you see in the diagram in Figure 4-1 the ground state $5s_{1/2}$ has two hyperfine levels and $5p_{3/2}$ has four.

Figure 4-2 shows the spectra of the transitions starting from the upper ground state hyperfine level of ^{87}Rb and ^{85}Rb. These signals were produced using Doppler-free saturation spectroscopy.

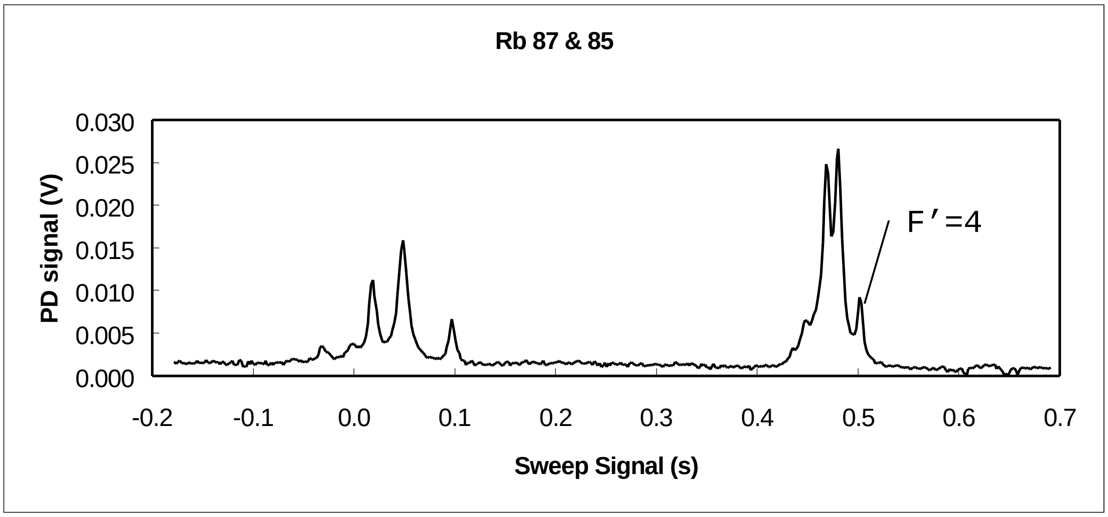


Figure 4-2: Spectra of rubidium 85 & 87

We will use the peak labeled F′=4 (F′ denotes the upper level) of the spectrum of the isotope of ^{85}Rb to frequency lock our laser, but we could just as well use ^{87}Rb it we want to cool that isotope.

Although we tune the laser to excite the electrons from the F=3 to the F′=4, there is a very small chance that some of the atoms will be excited to the F′=3 level and fall back down to the F=2 level (quantum selection rules which state that $\ddot{A}F = 0 \text{ or } \pm 1$) and will not be excited any more by our laser. We use the microwave side band mentioned in Chapter 2 to produce light resonant with the F=2 to F′=3 transition so as to re-pump these electrons back to the F′=3 level. From there they can decay back to the F=3 where they will be cooled.

4.3 Frequency Locking the Laser

We modulate the laser frequency by injecting a small sinusoidal current with a frequency of approximately 90kHz. This modulation will distort the spectrum a little, producing a modulation wherever the slope is not zero. We then send the photodetector signal from the Doppler-free absorption spectrometer into the lock-in amplifier. The lock-in measures the amplitude and sign of the signal modulation which is proportional to the derivative of the spectrum signal. If we look at the spectrum after it has been sent through the lock-in amplifier, top trace in Figure 4-3, we see that the steeper the slope in the absorption spectrum the bigger the signal from the lock-in amplifier.

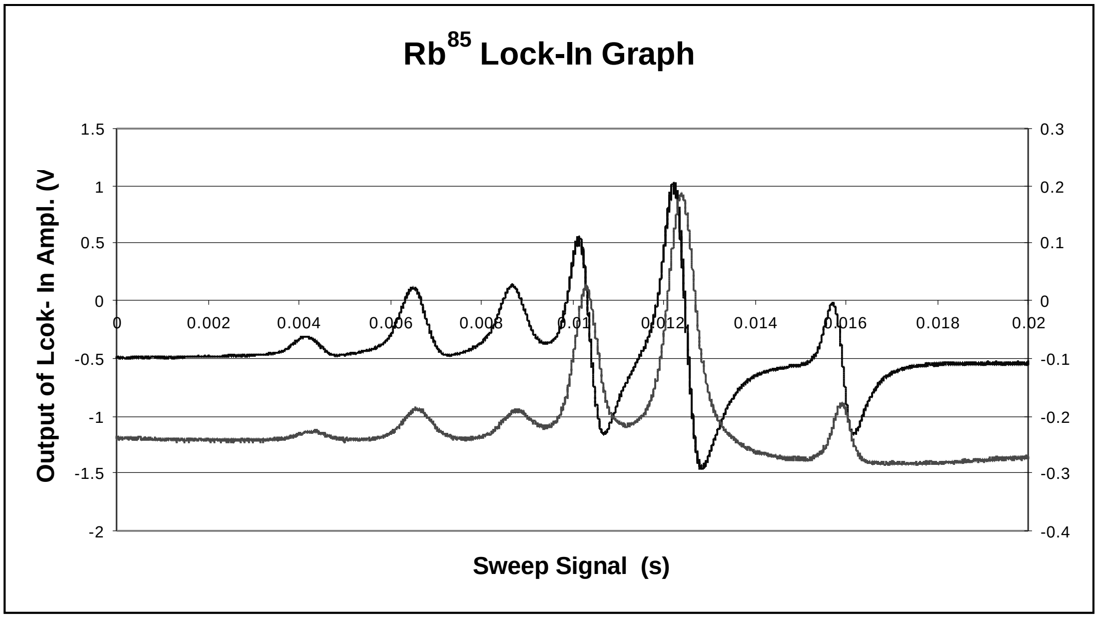


Figure 4-3: 85Rb Spectrum with amplified slope received from the lock in Amplifier

We lock the laser in the following method. First we manually set the laser frequency to the lock point (peak F=3). Then we connect the lock-in output to the input of the laser piezo control. This acts as negative feedback that will create a restoring force that causes the laser to stay locked onto the point where the slope equals zero as measured by the lock-in amplifier.

Chapter 5

Measuring the Temperature of Cold Atoms

5.1 Time of Flight

In this final chapter, I will discuss temperature determinations using three different models. We measure the temperature of the atoms using a Time of Flight (TOF) technique. TOF describes the velocity measurement by observation of the expansion of a cloud of cold atoms once they are released from a trap. The Root Mean Square(RMS) average velocity of the atoms is related directly to the temperature of the atoms by the following equation:

$$\frac{1}{2}m\bar{v}^2 = \frac{3}{2}k_B T \quad (1)$$

Equation 1 is a consequence of the ideal gas law where v is the average velocity of the cloud of atoms, k_B is Boltzmann constant, m is the mass of the atoms, and T is the temperature. You see that the larger the velocity the higher the temperature, and vice versa, the smaller the velocity the lower the temperature.

We can observe the expansion of the atoms using a probe laser beam. Because the cloud is inside an evacuated chamber, once the MOT is turned off, gravity will accelerate the cloud downward toward the probe beam. As the cloud of atoms falls through the beam, it will give off fluorescence. Figure 5-1 is a diagram of the cloud of atoms as they fall through the probe beam. Notice that there are no magnetic coils or trapping beams shown. This is because we must turn off the trapping beams and the magnetic coils in order to measure the temperature. As you see in the Figure 5-1, we use special lenses to capture the fluorescence, and record it with a photodetector. Figure 5-2 is a typical graph of a fluorescence signal received from the photodetector.

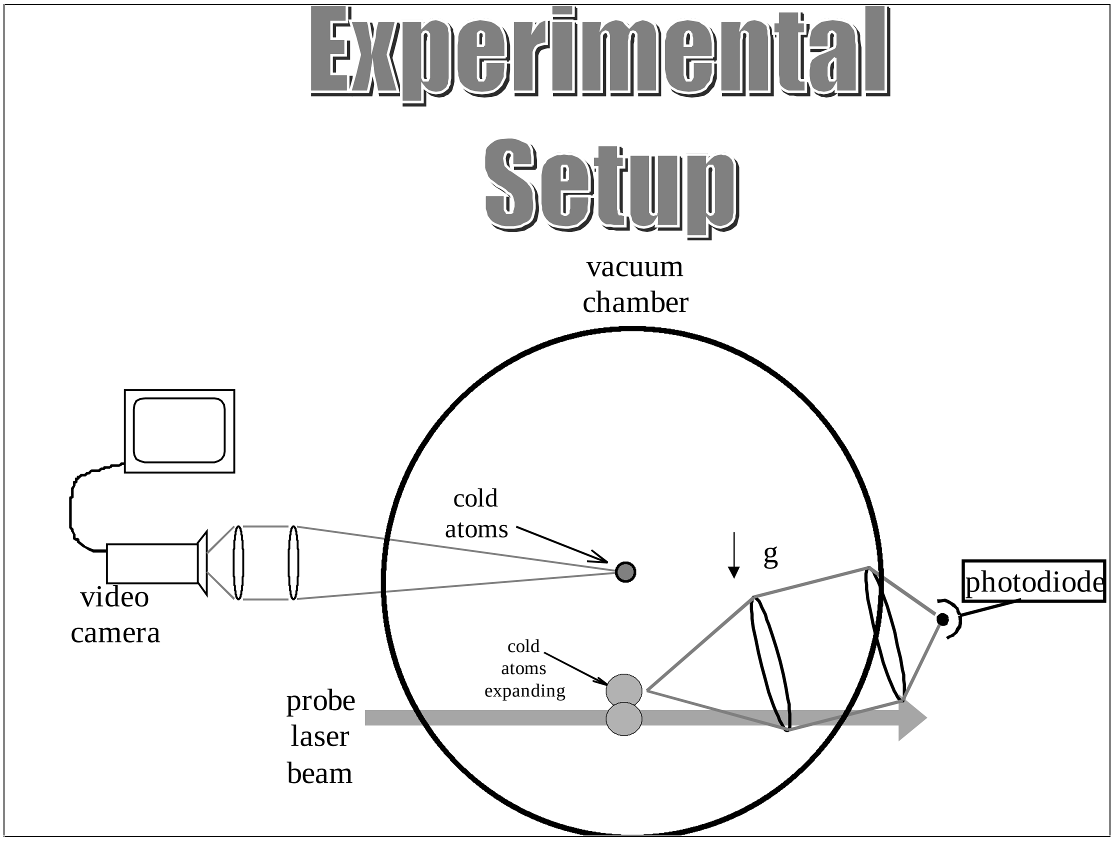
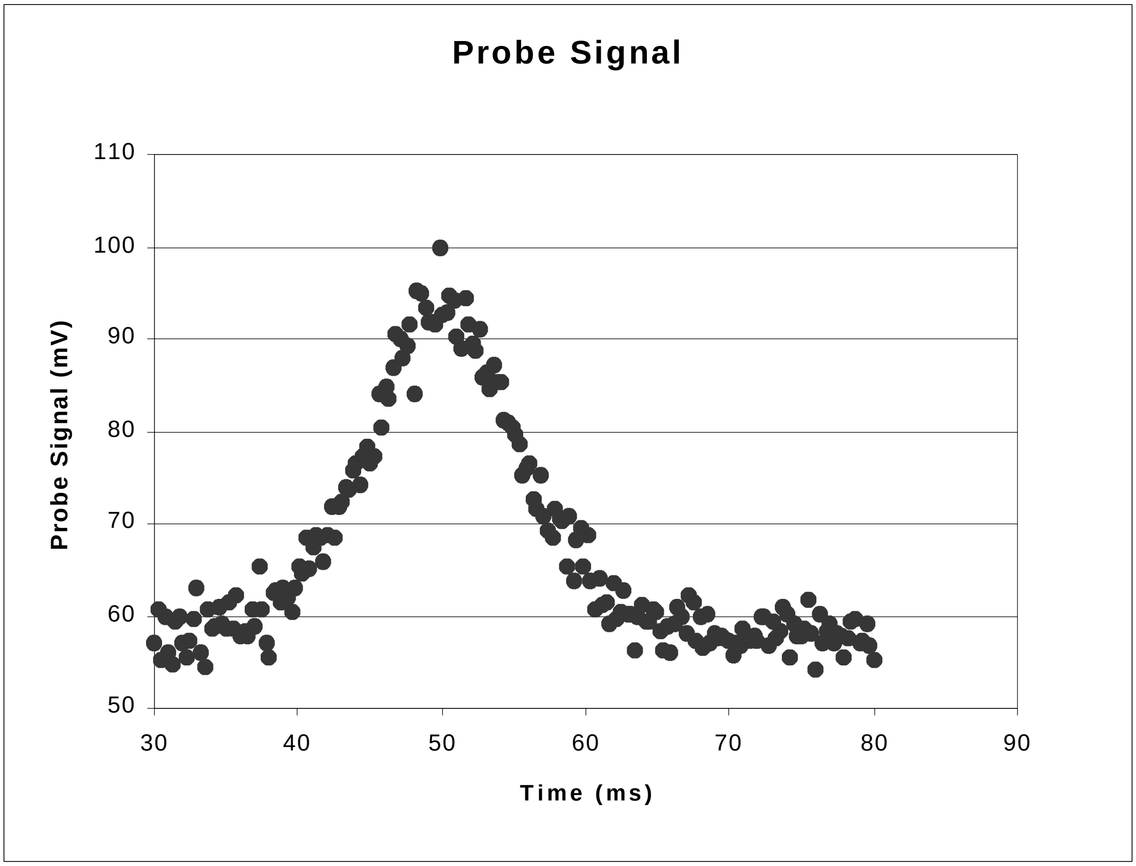


Figure 5-1 Diagram of falling atoms passing through probe beam and captured with a photodetector

Figure 5-2: Fluorescence signal receive as the atoms fall through the probe beam



The fluorescence signal is approximately a Gaussian distribution, known for its bell curve appearance. This appearance is expected because Maxwell’s theory on the distribution on molecular speeds tells us that molecules in a gas have a variety of speeds. The characteristic mathematical equation that relates to this distribution is:

$$I = A \times e^{-b^{2}} \tag{2}$$

We use equations of this form in an Excel spreadsheet to produce a fitted curve to the fluorescence signal, and hence calculate the temperature of the atoms. As mentioned in earlier chapters, the temperature is important to our experiments because the atoms must have small momentum and thus a large wavelength so that they will scatter off the magnetic surface at large angles.

When measuring the temperature of atoms, there are two approaches we can use. We can either measure the atoms far away from the trap's central position (short TOF) or relative close to the central position (long TOF). What I mean by long TOF compared to short TOF is that the fall time is at least five times greater than the ratio $\frac{\text{Initial Cloud Radius}}{\text{Thermal velocity}}$ for long TOF.

In previous work, the temperature of the cloud of atoms was measured using the long TOF model, which is mathematically simpler. Although the long TOF gives us a very good measurement, we unfortunately can not use this model in our lab. Our present lab setup has limitations; we do not have the luxury of allowing the cloud of atoms to fall over a very long distance. The current arrangement has been designed with space to allow the atoms to be launched upwards rather than to fall.

In order to get a very clear understanding of TOF, I will now discuss and compare short and long TOF. I will model three different scenarios; the first two will represent a long TOF, and the final one a short TOF. The first model will be the simplest one. As I move to the second and third models, I will include more physical properties of the expanding cloud.

5.2 Model 1

We start with a cloud of cooled atoms that has been allowed to expand for a time *t*, beginning from an infinitesimal point. Its density along the z axis has the form:

$$\frac{dn}{dz} \propto \frac{1}{\mathrm{a}t} \times e^{-\frac{z^2}{\mathrm{a}^2 t^2}} \qquad (3)$$

$$\text{with } T = \frac{\mathrm{a}^2 m}{2k} \qquad (4)$$

where a is the most probably speed, and *z* is the vertical distance from the center of the cloud. As the cloud falls through the probe beam, it gives off fluorescence intensity *I* proportional to the density of the cloud at the point where the probe beam strikes. If you look at the graph in Figure 5-2, alpha is proportional to the width of the bell shaped curve. Equation 5-3 is actually a modified version of a 3-dimensional Maxwellian integrated over the x and y velocities [Roach pg. 58]. Finding a is the key to calculating the temperature of the cloud of atoms as shown by Equation 5-4. We use a least-squares fit to calculate the value of a from our data.

We now consider the cloud at some time after the trap is turned off and the cloud passes through the probe beam. We assume both that the cloud’s velocity along z is constant and that the cloud of atoms is not expanding during the short time that it falls through the probe beam. Thus, in Equation 3 we replace t with the constant value t_0, the time center of cloud reaches the probe beam. The cloud's downward velocity at this point is therefore:

$$v_o = gt_o \tag{5}$$

Now that we know the speed, we also know that z (the coordinate of the piece of the cloud being probed) at some time later is equal to

$$z = v_o(t - t_0) \tag{6}$$

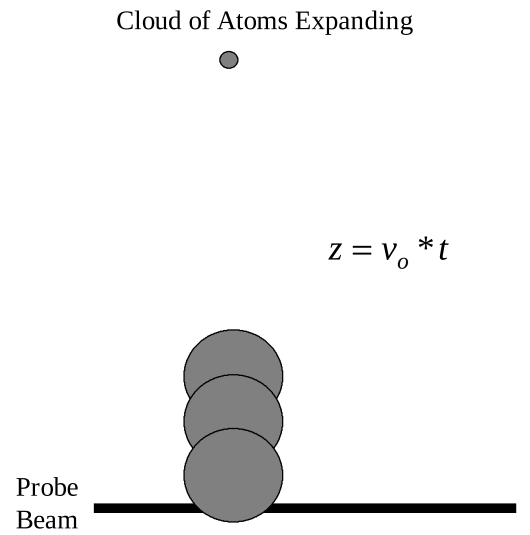
We now have everything to develop our equation that will represent the intensity of fluorescence emitted by the cloud of atoms s a function of time for Model 1. In order to prepare the equation for our spreadsheet, we will first put Equation 5 and 6 into Equation 3. Next we let $A = \frac{v_o}{a}$, and $C_1 = \frac{v_o}{a t_o}$. Thus we get an expression for the photodetector signal:

$$Signal = N(t) = Offset + C_1 \times e^{-\left(\frac{A(t-t_o)}{t_0}\right)^2} \tag{7}$$

The offset is added because the scattered laser light does not make it to the photodetector.

Model 1

- •Initial cloud size is negligible
- •Cloud is not accelerating
- •Cloud does not expand as it passes through the probe beam
- •Thickness of probe beam is ignored



$$Signal = N(t) = Offset + C_1 \times e^{-\left(\frac{A(t-t_o)}{t_0}\right)^2}$$

$$T = \frac{g^2 t^2 m}{2Ak}$$

Figure 5-3: Summary of Model 1

If you look at figure 5-3, I summed up the important points of model one. Notice that we are not neglecting the fact that the cloud of atoms is expanding; we are saying that as it passing through the beam the expansion is negligible. We are neglecting the initial size of the cloud because the cloud has fallen so far that the initial size cloud is very small compared to the cloud once it has expanded.

We use a fluorescence signal from previous work to test our theory. In our Excel spreadsheet we fit a curve to the fluorescence signal. We have unknown parameters: Offset, the constant C_1, a, and. We compared our temperature to the temperature using a similar model from previous work, and we get the same value, 26.7 $\mathrm{m}K$. [Roach, pg. 58] One would think that since the temperature is the same we could stop here, but as mentioned earlier, we have neglected some very important physics. This model is still for a long TOF, which will not be useful to us.

5.3 Model 2

In order to include more of the physical properties related the expanding cloud of atoms, we will not assume that the cloud of atoms is falling at a constant velocity. We will still make the assumption that the initial cloud size can be neglected, but we will allow the cloud to expand as it passes through the probe beam. Now as the cloud falls the position at some later time t is:

$$z = -\frac{1}{2} g t^2 + z_o \tag{8}$$

where z_0 is the distance from the probe to the trap center. To correct equation 5-3 all we have to do is replace the old z with this new z, and we would get an expression for the photodetector signal as:

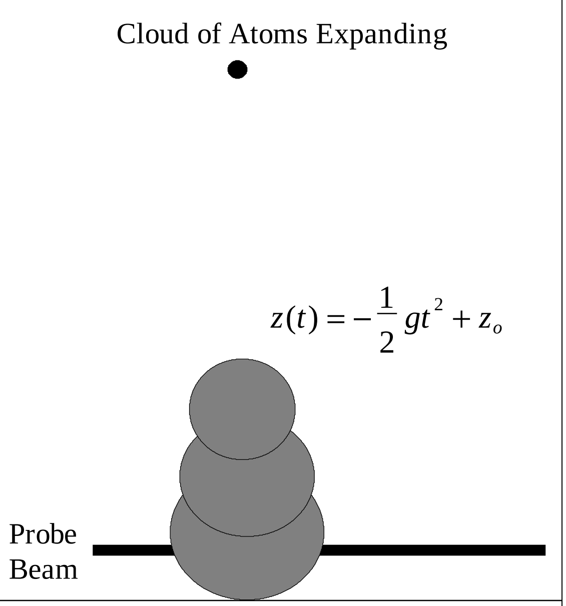
$$N(t) = Offset + \frac{C}{t\mathrm{a}} \times e^{-\left(\frac{\frac{1}{2} g t^2 - z_o}{\mathrm{a} t}\right)^2} \tag{9}$$

This time in our excel spreadsheet we do not substitute A for $\frac{v_o}{\mathrm{a}}$ but we do include the initial velocity of the cloud of atoms, v_o, into the constant parameter and T is calculated using Equation 5-4.

Figure 5-4 is a quick outline of Model 2. Our temperature measurement using Model 2 is 27.25 $\mathrm{m}K$, which is slightly higher. We do not expect the temperature value for Model 1 to change much than Model 2, and we see it does not.

Model 2

- Initial cloud size is negligible
- Cloud is accelerating
- Cloud expands as it passes through the probe beam
- Thickness of probe beam is ignored



$$z(t) = -\frac{1}{2}gt^2 + z_o$$

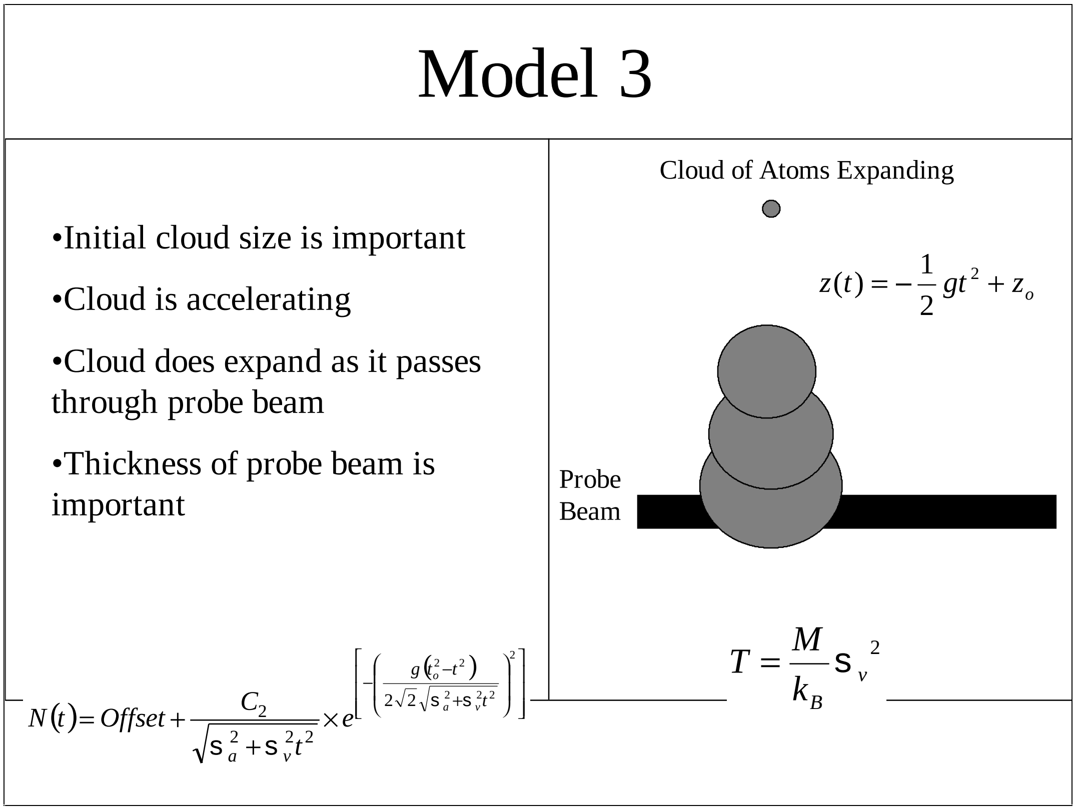
$$N(t) = Offset + \frac{C}{t^{\alpha}} \times e^{-\left(\frac{\frac{1}{2}gt^2 - z_o}{\alpha t}\right)^2}$$

Figure 5-4 Summary of Model 2

5.4 Model 3

The description of our final model schematically looks the same as Figure 5-3 except, notice that I illustrate Model 3 is a shorter TOF by decreasing the distance between the probe beam and the initial cloud size (See figure 5-5). I also increase the width of the probe beam to show that we are not going to neglect it in this model. So, in this final model, we include every possible physical aspect of the cloud of falling atoms. As you will see in this short

TOF the profile and shape of the probe laser beam becomes very important. What I mean by profile is that the light coming from the probe beam has a Gaussian distribution just as the cloud of atoms, so when the atoms fall through the probe laser beam the two distributions will overlap creating what is mathematically called a convolution. The physical cross-section of the beam, whether it is tall vs. short or wide vs. narrow, will also be important in calculating a fit to the fluorescence signal. A very short and wide probe beam works best for reason I will discuss shortly.



Model 3

- Initial cloud size is important
- Cloud is accelerating
- Cloud does expand as it passes through probe beam
- Thickness of probe beam is important

$$z(t) = -\frac{1}{2}gt^2 + z_o$$

$$N(t) = Offset + \frac{C_2}{\sqrt{\sigma_a^2 + \sigma_v^2 t^2}} \times e^{\left[-\left(\frac{g(t_o^2 - t^2)}{2\sqrt{2}\sqrt{\sigma_a^2 + \sigma_v^2 t^2}}\right)^2\right]}$$

$$T = \frac{M}{k_B}\sigma_v^2$$

Figure 5-5: Summary of Model 3

The mathematical expression for Model 3 [Brzozowski et al., 2002] is:

$$N(t) = \frac{P_o}{2\pi\left(\sqrt{\left(\sigma_{Ix}^2 + \sigma_t^2\right)\left(\sigma_{Iy}^2 + \sigma_t^2\right)}\right)} * e^{\left[-\left(\frac{g\left(t_o^2 - t^2\right)}{2\sqrt{2}\sqrt{\left(\sigma_{Ix}^2 + \sigma_t^2\right)}}\right)^2\right]} \tag{10}$$

$$\text{with } T = \frac{M}{k_B}\sigma_v^2 \tag{11}$$

P_o is the power of the probe laser beam; t_o again is the time the center of the cloud reaches the probe beam and σ_{Ix} and σ_{Iy} are the Gaussian beam radii along the x (vertical and y (horizontal) axes. $\sigma_t = \sqrt{\left(\sigma_o^2 + \sigma_v^2 t^2\right)}$ is the Gaussian radius of the ballistically expanded cloud of atoms, where σ_o is the initial Gaussian radius of a spherically symmetric cloud of atoms, and $\sigma_v = \alpha/\sqrt{2}$ is the thermal velocity. In the limit when the cloud is expanding over a long distance $\sigma_o << \sigma_v t$ and $\sigma_{Ix}, \sigma_{Iy} << \sigma_v t$, Equation 5-10 becomes:

$$N(t) = \frac{P_o}{2\pi\sigma_v^2 t_o^2} \times e^{\left[-\left(\frac{g\left(t - t_0\right)}{\sqrt{2}\sigma_v}\right)^2\right]} \tag{12}$$

Equation 5-12 is essentially the same as Equation 5-7 with $C_1 = \frac{P_o}{2\pi\sigma_v^2 t_o^2}$ and $\frac{A}{t_o} = \frac{g}{\sqrt{2}\sigma_v}$, except there is no offset. Note that in the denominator of the prefactor, t , has been replaced with t_o because the two are approximately equal during the interaction.

Earlier I stated that we will use a short flat probe laser beam to measure the temperature cloud of atoms. It does not require a lot of physics to understand that a very short and wide flat probe beam will give us the best fluorescence signal of the cloud of falling atoms; this is because the wide beam will illuminate nearly all the atoms.

Now if we model a short TOF that means that $\sigma_{Iy} >> \sigma_t$, so equation 5-10 becomes: $N(t) = Offset + \frac{C_2}{\sqrt{\sigma_a^2 + \sigma_v^2 t^2}} \times e^{\left[-\left(\frac{g\left(t_o^2 - t^2\right)}{2\sqrt{2}\sqrt{\sigma_a^2 + \sigma_v^2 t^2}}\right)^2\right]}$

(13)

where $\sigma_a = \sqrt{\sigma_o^2 + \sigma_{Ix}^2}$ represents the effective width of the cloud and the probe beam and the constant $C_2 = \frac{P_o}{\sigma_{Iy}\sqrt{2\pi}}$. The most noticeable difference between the Equation 5-9 and Equation 5-13 is that we add σ_a in as a parameter, which accounts for the importance of the initial cloud size and the probe beam size. The temperature measurement that we get from this model is 21.09 μK .

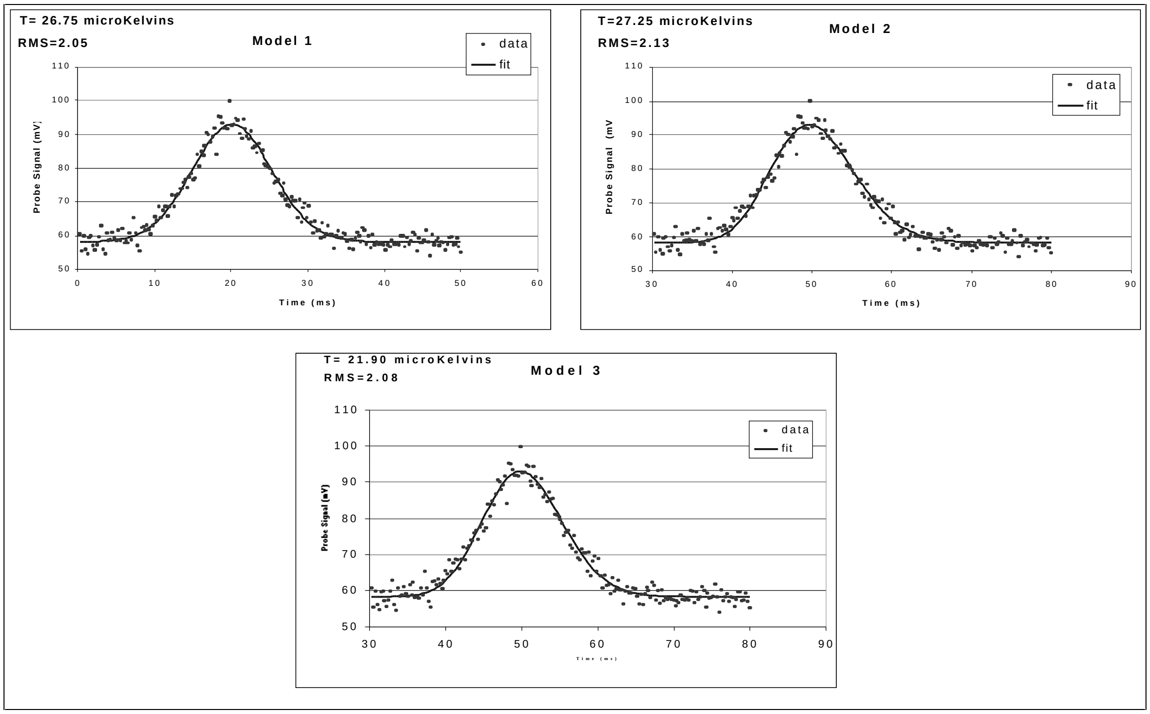


Figure 5-6: Temperature values

5.5 Comparison of the Three Models

Model 1	Model 2	Model 3
•Initial cloud size is negligible •Cloud is not accelerating •Cloud does not expand as it passes through probe beam •Thickness of probe beam is ignored •T = 26.75 microKelvins •RMS = 2.05	•Initial cloud size is negligible •Cloud is accelerating •Cloud expands as it passes through probe beam •Thickness of probe beam is ignored •T = 27.25 microKelvins •RMS = 2.13	•Initial cloud size is important •Cloud is accelerating •Cloud expand as it passes through probe beam •Thickness of probe beam is important •T = 21.09 microKelvins •RMS = 2.08

Figure 5-7 Three Models

Before I begin to review the three models, see Figure 5-7 for a summary. To analyze the accuracy of the three models we measure the average distance that the data points are away from our fit (RMS deviation), and we see that Model 1 has the lowest RMS deviation as shown in Figure 5-7. The lower the RMS value the better the fit. All of the values are low, meaning they are about the size of the RMS deviation when no signal is present. The reason that Model 1 fits best is unclear to us. The RMS value of Model 3 is lower that Model 2 which is no surprise because mathematically, adding an extra parameter should make a fit better. Comparing all the models, the temperature for Model 3 is the lowest, and considerably less than for the other two. Though all the models fit the data very well, we conclude that we should not ignore the probe laser beam and the initial cloud sizes because they will definitely affect the temperature. Model 3 provides an important increase in accuracy for our future temperature measurements.

References

Brzozowski, Tomasz M.; Gawlik, Wojciech; Maczynska, Maria; Zachorowski, Jerzy; Zawada, Michal, Time-of-flight measurement of the temperature of cold atoms for short trap-probe bean distances, Institute of Physics Publishing, Journal of Optics B:Quantum and Semiclassical Optics. 62-66, 2002.

Chu, Steven, *Laser Trapping of Neutral Particles,* Scientific American, 71-76, February 1992.

Cohen-Tannoudji, Claude N. and Phillips, William D., *New Mechanisms for Laser Cooling*, Physics Today, October 1990, 33-40.

Griffiths, David J, *Introduction to Quantum Mechanics.* Prentice Hall, New Jersey, 1995.

Kaminow, Ivan P. and Siegman, Anthony E., *Laser Devices and Applications.* Institute of Electric and Electronic Engineers, New York, 1973.

Metcalf, Harold J., and Phillips, William D., *Cooling and Trapping Atoms*, Scientific American, 50-56, March 1987.

Ohanian, Hans C., *Modern Physics second edition.* Prentice Hall, New Jersey, 1995.

Roach, Timothy M., *Interaction of Laser-Cooled Atoms and Magnetic Surfaces,* unpublished dissertation. Yale Graduate School, May 1996.