Imaging of Ultracold Atomic Populations in Magneto-optical Traps

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Spring, 2007
Abstract

This research attempted to characterize a magneto-optical trap (MOT) through absorption and fluorescence imaging. During the summer of 2006, work was undertaken in the Remote Sensing Division at the Naval Research Laboratory in Washington, DC to construct the imaging systems. The fluorescence system measured a trapped atomic population of $8.8 \times 10^6$ atoms, while the more accurate absorption system indicated a trapped population of $4.6 \times 10^6$ atoms. However, due to the very large imprecision in the fluorescence imaging values, these values are considered to be in agreement with one another, indicating that the imaging systems were functioning. Additional work will allow a time of flight measurement to determine the temperature of the trapped population and the precision of the absorption imaging system. The imaging systems will also be used for analysis of a Bose Einstein Condensate that the laboratory is in the process of creating.
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Chapter I: Introduction

1.1 Motivation

The study of ultracold atoms has become one of the most interesting and dynamic in physics, with Nobel prizes awarded in 1997 and 2001 for work done in the field. There is great potential for further investigation in this area of some fundamental atomic physics, as well as practical applications. Atom interferometry provides one of the primary motivations for the study of cold atoms. In a Bose Einstein Condensate (BEC), atoms are cooled until they collapse into a single quantum state. Techniques can then be used to separate and recombine the atomic population. Any phase shift between the two populations can be easily measured as an interference pattern. In particular, it is hoped that ultracold atoms can be used to detect slight changes in the gravitational field, allowing one to detect underground mineral deposits or other structures that would normally be undetectable. In a gyroscope, an atomic interferometer will be $10^{11}$ times more sensitive than current light interferometry methods. There is also hope that atom interferometers may be sensitive enough to detect additional terms in the law of gravity, as well as to study such phenomena as Berry’s phase and conduct a search for nonlinear terms in the Schrodinger equation [1,2]. The Naval Research Lab in Washington D.C. has an excellent cold atoms lab working towards these goals. The research in this thesis focused on the construction of an imaging system that would allow for precise calibration and measurement of a magneto-optic trap.
1.2 Overview

A magneto-optical trap (MOT) is the starting point for creation of a Bose-Einstein Condensate. Using red-detuned lasers and a magnetic field, while taking advantage of quantum selection rules, it is possible to cool atoms to a few hundred microkelvin, thus creating a MOT. Once this arrangement has captured cold atoms, it is necessary to characterize the properties of those atoms. There are two variables of particular significance: the number of atoms contained and their temperature. From collected images, it is possible to approximately determine the number of atoms in the MOT using the fluorescence of the atoms as they absorb and reemit photons from the cooling beams. A more sophisticated method of measurement is through absorption of a probe laser beam by the atom cloud. By sending a laser beam tuned to a transition frequency of the trapped atoms, and comparing the intensity of the beam after it exits the trap with the intensity of the laser when the trap is not operational, one can determine the absorption of the probe beam and therefore the size of the atomic population though Beer’s Law.

The time of flight measurement (TOF) allows one to determine the temperature of the trapped atom population. When one terminates the magnetic field and laser cooling, the atomic cloud begins to expand. By mapping the rate of expansion, it is possible to determine the velocity of the atoms and therefore the temperature of the cloud. The lifetime of an uncontained cloud is only a few milliseconds, requiring precise timing control. A probe laser is used once again. The absorption of the beam by the cloud allows one to chart the expansion of the atoms, allowing for a temperature calculation.
Chapter II
Theoretical Considerations

2.1 Laser Cooling and MOT Theory

Before a discussion of imaging can occur, it is necessary to briefly discuss the basics of atom cooling. Although there are several methods for cooling atoms, the system that is relevant in this case is the magneto-optic trap (MOT). The trap is a very effective and robust way to trap atoms at temperatures in the range of a few hundred microkelvin. A magneto-optic trap serves as a useful source for the cold atoms necessary for the creation of a Bose-Einstein Condensate, which is the eventual goal of the NRL Remote Sensing Division’s cold atom program.

A fairly standard configuration for the MOT, and the design used for the MOT in the Remote Sensing Division, involves three pairs of orthogonal laser beams, a repump laser and two anti-helmholtz coils to generate a magnetic field. The cooling and containment system of the MOT consists of the orthogonal laser beams, which cool the atoms, and the coils, which, in conjunction with the laser beams, create the necessary counter propagating spatial confinement. A schematic of the MOT is shown in Figure 1.
We will first discuss the cooling mechanism. Taking a single pair of the counter orthogonal lasers, we set the frequency of the laser beam below that of the resonance frequency of the atomic transition. Rubidium atoms make up the atomic population. The atoms are dispensed into a vacuum cell. The Rubidium-87 isotope is of particular interest because inexpensive lasers are available at the resonance wavelength of the atom. The atoms are not stationary but actually have some thermal velocity distribution, resulting in a Doppler shift of the laser beams in the reference frame of an atom. Because we have red-detuned the laser, the frequency of the lasers in the laboratory frame is lower than the resonance frequency of the atom. However, for those atoms moving towards an incoming laser beam, the Doppler shift may be sufficient that, in the frame of the atom, the photon’s frequency matches that of the resonance frequency. If the photon is absorbed by the atom, conservation of momentum requires that the atom decrease its velocity, i.e. cooling of the atom. The cooling mechanism is shown in Figure 2.
Mathematically, the physics discussed above can be modeled as a total force equation in which the net force is equal to the difference in the forces caused by absorption from each pair of laser beams. The light can be shown to exert a damping force on the atomic population and is the basis for the molasses technique. The force on the particle shown in Figure 2 can be expressed as

\[ F_{\text{molasses}} = F_{\text{scatt}}(\omega - \omega_0 - kv) - F_{\text{scatt}}(\omega - \omega_0 + kv) \]  

(2.1)

where \( \omega_0 \) is the resonance frequency of the atom, \( \omega \) is the frequency of the laser, and \( kv \) is the effect of the Doppler shift on the frequency of the laser in the rest frame of the atom [2].

Performing a first-order Taylor expansion on the equation above, we get:

\[ F_{\text{molasses}} = F_{\text{scatt}}(\omega - \omega_0) - \frac{\partial F}{\partial \omega} kv - \left[ F_{\text{scatt}}(\omega - \omega_0) + kv \frac{\partial F}{\partial \omega} \right] \]  

(2.2)

\[ F_{\text{molasses}} = -2 \frac{\partial F}{\partial \omega} kv = -\alpha v \]

Thus, the net force for low velocity atoms varies linearly with velocity and opposes the motion, thereby damping the particle. The force as a function of velocity is the product of
the photon’s momentum and the number of photons absorbed and then scattered by the atom. The scattering rate can be described as

\[ R_{\text{scat}} = \Gamma \rho_2 = \frac{\Gamma}{2} \frac{\Omega^2 / 2}{\delta^2 + \Omega^2 / 2 + \Gamma^2 / 4} \]  

(2.3)

where \( \Gamma \) is the decay rate of the excited state, \( \rho_2 \) is the fraction of the population in the excited state, \( \delta \) is the frequency detuning of the cooling laser and \( \Omega \) is the Rabi frequency [2]. The expression for \( \rho_2 \) is obtained from the optical Bloch equations.

The scattering force merely requires the multiplication of the scattering rate by the momentum of the photon:

\[ F_{\text{scat}} = \hbar k \frac{\Gamma}{2} \frac{\Omega^2 / 2}{\delta^2 + \Omega^2 / 2 + \Gamma^2 / 4} \]  

(2.4)

Taking the derivative of this expression with respect to frequency, we solve for the damping constant, obtaining

\[ \alpha = 2k \frac{\partial F}{\partial \omega} = 2 \hbar k^2 \frac{-2\delta}{\delta^2 + \Gamma^2 / 4} R_{\text{scat}} \]  

(2.5)

The graph of force as a function of velocity is shown in Figure 3. The dotted lines are the forces from each laser and the solid line is the total force. Notice that the force is in the opposite direction of the motion.
Figure 3: This graph shows the force as function of velocity. Notice that force always opposes velocity [2].

The photon is re-emitted when the atom de-excites; however, because the direction of this spontaneous emission is random, the net change in momentum from the spontaneous emission is zero. In reality, this establishes a cooling lower limit. A simple momentum and energy calculation shows that, at the very time a photon is absorbed or emitted, it causes a change in the velocity of the rubidium atom of .6 cm/s. Thus, it is extremely difficult to cool an atom below this velocity increment.

An excellent feature of the MOT is that it does not require particularly precise calibration or alignment. However, the MOT can only capture a small fraction of room temperature atoms. This capture rate can be calculated from the force exerted on the atomic population, given by

\[ F_{\text{max}} = \hbar k \gamma = \hbar k \Gamma / 2 \]  \hspace{1cm} (2.6)

where \( \gamma \) is defined as the pumping rate and can be rewritten as \( \Gamma / 2 \), and \( k \) is the frequency detuning of the cooling beam [4]. The average force of the system is approximated as being half of the maximum force:

\[ F_{\text{avg}} = \hbar k \Gamma / 4 \]  \hspace{1cm} (2.7)
When an atom enters the trap, the force applied over the length of the trap must be sufficient to stop the motion of the atom. Thus the force multiplied by the distance of the atom’s path through the trap must be equal to the kinetic energy of the atom:

\[ \frac{1}{2} m v^2 = F_w L = \frac{1}{4} \hbar k \Gamma L \]  \hspace{1cm} (2.8)

The maximum velocity is given by

\[ v = \sqrt{\frac{\hbar \Gamma L}{2m}} \]  \hspace{1cm} (2.9)

It is now possible to solve for the velocity of the atom and determine the velocity trap limit. This limit provides a useful confirmation of our TOF measurement, which will be discussed shortly. A TOF measurement that determines a velocity that is greater than the trap limit indicates an erroneous TOF measurement.

The capture velocity sets an upper bound on the temperature of the MOT. The Doppler cooling limit can be calculated to determine a lower bound. A trapped atom will scatter some number of incident photons at a rate \( R_{\text{cat}} \). The scattering is in a random direction and thus causes the velocity of the atom to evolve as a random walk.

Mathematically, the scattering causes the mean squared velocity of the atom to increase with time, as given by equation 2.10.

\[ \left( \bar{v}_z^2 \right)_{\text{scat}} = \eta v_r^2 R_{\text{scat}} t \]  \hspace{1cm} (2.10)

The coefficient \( \eta \) adjusts for the fact that, in this equation, we are dealing only with the change in the velocity along the z-axis. Assuming that the system is symmetrical along the axis this factor is 1/3. The \( v_r \) is the recoil velocity of the atom caused by the photon emission. There is also the absorption fluctuation caused by differences in the rate at which an atom absorbs photons from the laser beam. This fluctuation in the rate causes a random
walk of the $z$-axis component of the velocity. There is therefore no need for the coefficient $\eta$.

$$\left\langle v_z^2 \right\rangle_{\text{abs}} = v_z^2 R_{\text{scat}} t \quad (2.11)$$

This random walks occurs in addition to the damping force generated by the MOT cooling lasers. After combining equation 2.10 and 2.11 and accounting for the damping force from the cooling beams, the time evolution of average energy of the atom is given by

$$\frac{1}{2} M \frac{d\overline{v_z^2}}{dt} = \frac{1}{2} Mv_r^2 (1 + \eta)(2R_{\text{scat}}) - \alpha v_z^2$$  \quad (2.12)

where we have introduced a factor of 2 in the scattering rate to account for the fact that there are two counter-propagating beams in our MOT construction. At the Doppler cooling limit, the left side of the equation is equal to zero, leading to the expression

$$\overline{v_z^2} = \frac{2Mv_r^2 R_{\text{scat}}}{\alpha}$$  \quad (2.13)

In this expression we set $\eta$ equal to 1, as scattering in either of the other two directions will on average impart a third of the impulse in the $z$ direction. Thus the total value of $\eta$ is equal to one when we sum over the three dimensions.

Applying equation to 2.5 to 2.13 and using the equipartition theorem to convert from velocity to temperature, we obtain the expression

$$k_B T = \frac{\hbar \Gamma / (1 + (2\delta / \Gamma)^2)}{4 \left( -2\delta / \Gamma \right)}$$  \quad (2.14)

This expression is minimized when the detuning of the beam is equal to $-\Gamma / 2$. In that case, the Doppler limited temperature is given by

$$T = \frac{\hbar \Gamma}{2k_B}$$  \quad (2.15)
For Rubidium 87, this temperature value is 144 microkelvin. This limit can be overcome using polarization gradient cooling [5]. However, a rigorous treatment of this technique is beyond the scope of this investigation.

Besides cooling, it is also necessary to confine the atomic population to a relatively small volume. In our case, this volume was only a few millimeters in diameter. This confinement is accomplished by combining the magnetic field and laser beams. Consider a system in which the atoms have already reached their cooling limit, and thus Doppler effects are negligible. The magnetic field generated by the anti-helmholtz coils causes a magnetic null midway between the two coils along the cylindrical axis. Around this null, the magnetic field varies linearly. This magnetic gradient creates a varying potential for atoms of different spin. The resulting potential is shown in Figure 4.

![Figure 4: The Zeeman splitting and quantum selection rules allow the construction of a potential with a minimum in the center of the MOT [6].](image)

To achieve trapping, the photons are red-detuned and thus have lower energy in the lab frame. We can use the Zeeman splitting caused by the magnetic field and the polarization of the light to ensure that atoms along the +z direction absorb more photons traveling in the -z
direction, and vice versa, as is shown above. Generalizing to three dimensions, it is apparent that atoms are pushed to the center of the trap.

Mathematically, we can now incorporate the Zeeman shift of the potential into the frequency parameter that determines the scattering force function. This is done using equation 2.16 [2].

\[
F_{\text{molasses}} = F_{\text{scatt}}^\omega (\omega - \omega_0 - kv - Bz) - F_{\text{scatt}}^\omega (\omega - \omega_0 - kv + Bz)
\]

\[
(2.16)
\]

\[
F_{\text{molasses}} = -2 \frac{\partial F}{\partial \omega} kv + 2 \frac{\partial F}{\partial \omega_0} Bz = -2 \frac{\partial F}{\partial \omega} (kv + Bz)
\]

We introduce a negative sign in the magnetic field term when we change the derivative from \(\partial \omega_0\) to \(\partial \omega\). This makes sense if we realize that what actually determines the force function is the difference between the resonance and photon frequencies \((\delta = \omega - \omega_0)\).

The introduction of the magnetic field thus creates a force that not only dampens the motion of the atoms, but also drives the atoms towards the magnetic null at the origin of the trap.
2.2 Visualization Theory:

There are two standard methods for imaging atoms in the MOT in order to determine their number and temperature, fluorescence imaging and absorption imaging. Fluorescence imaging tends to be simpler. It involves little more than a CCD camera used to measure the intensity of fluorescence caused by the de-excitation of the atoms as they interact with the cooling beams. Absorption imaging is more involved and requires construction of a significant optical system. It uses a probe beam laser set at the resonance frequency of the Rb-87 F=2 to F'=3 transition as shown in Figure 10. The beam enters the MOT and the intensity of the beam decreases as it passes through the atomic cloud. The standard volume element is a cylinder of length of dx, as shown in Figure 5.

\[
\frac{dI}{dx} = -\hbar \omega \gamma_p n \quad (2.17)
\]

where \( \gamma_p \) is the scattering rate of the photon and \( n \) is the density per unit volume [6].
Using the relation of the scattering rate for a low intensity beam that does not saturate the system, we obtain

\[ \gamma_p = \frac{s_0 \gamma}{2} \]  \hspace{1cm} (2.18)

where \( \gamma \) is the decay rate of the excited state and \( s_0 \) is the on resonance saturation parameter given by \( \frac{1}{I_\text{s}} \) [6]. The saturation intensity \( I_\text{s} \) is given by

\[ I_\text{s} = \frac{\pi \hbar c}{3\lambda^3 \tau} \]  \hspace{1cm} (2.19)

where \( \tau \) is the lifetime of the excited state [6].

Inserting our known values for the saturation parameter and \( \gamma_p \), we obtain the following differential equation

\[ \frac{dl}{dx} = -\sigma_{eg} nI \]  \hspace{1cm} (2.20)

where \( \sigma_{eg} \) is the cross section for scattering resonant light [6]. This is given by

\[ \sigma_{eg} = \frac{\hbar \omega}{2I_\text{s}} \]  \hspace{1cm} (2.21)

For Rb-85, which is very similar in properties to Rb-87, the cross sectional value is \( 290.7 \times 10^{-15} \text{ m}^2 \) [6]. Solving the differential equation 2.20, we obtain

\[ I(x) = I(0)e^{-\sigma_{eg}ax} \]  \hspace{1cm} (2.22)

Inserting the known parameters, we can now solve for the density of the MOT. Once the density is determined, we multiply by the volume of the cloud, and obtain the number of atoms trapped by the MOT.
After the number of atoms has been determined, it is relatively easy to determine the
temperature. An expansion of the ultracold atomic cloud occurs when the magnetic field and
cooling coils are shut down. The potentials previously discussed are therefore removed and
the atomic cloud expands outward from the magnetic null. At some variable time $\Delta t$ after
the MOT apparatus has been shut down, the probe beam is activated for a very short time,
usually on the order of a few microseconds. This is imaged with the camera. The result is an
absorption image from which the cloud size can be determined. The probe beam disperses
the ultracold atom population, but the resulting absorption is recorded by a CCD camera. By
varying the duration of $\Delta t$, it is possible to chart the expansion of the ultracold atomic
population as a function of time by studying the recorded images. The larger the value of $\Delta t$,
the greater the area over which the CCD should detect absorption. The CCD image will give
an indication of the distance the atomic cloud expands as a function of time. This can be
used to estimate velocity. While the derivation is not trivial, it can be shown that a Gaussian
atomic cloud with an initial distribution along a given direction characterized by $\sigma_0$ will
evolve into a Gaussian characterized by $\sigma_n$, with the relationship

$$\sigma_n^2 = \sigma_0^2 + \frac{k_B T}{m} \Delta t^2$$

(2.23)

where $T$ is temperature and $m$ is the mass of the particle in question [4].

As stated earlier, fluorescence imaging is much simpler. However, it lacks precision.
Several assumptions about the MOT cloud must be made to allow for a tractable equation.
Small measurement errors in some of the parameters needed for a fluorescence calculation
can greatly change the calculated value. Order of magnitude errors are not uncommon.
Beyond these issues, fluorescence imaging requires that the cooling beams be maintained
during the imaging. This prevents an accurate TOF measurement. Thus, fluorescence imaging is best used as a quick confirmation of the absorption imaging results.

A lens some distance $L$ from the MOT is used to capture a fraction of the fluorescence caused by the cooling beams and focuses the fluorescence onto a CCD chip. For a lens with diameter $D$, the total fluorescence per unit time is given by

$$\Phi = 16 \frac{L^2}{D^2} P$$

(2.24)

where $P$ is the power recorded by the CCD. This can be calculated by determining the number of photons recorded by the CCD in per unit time and multiplying this value by the energy of the photon, determined by

$$E_{\text{Photon}} = \frac{hc}{\lambda}$$

(2.25)

We must also obtain the relevant cross-section for the atom-photon interaction. This cross section is given by

$$\sigma = \sigma_0 \frac{1}{1 + \left(\frac{\delta}{\gamma/2}\right)^2 + \frac{I}{I_s}}$$

(2.26)

where $\delta$ is frequency detuning of the cooling beam, $I$ is the intensity of the cooling beam, $I_s$ is the saturation intensity, and $\gamma$ is the linewidth of the transition [2]. The number of atoms trapped by the MOT can now be solved for using the relation

$$N = \frac{\Phi}{61\sigma}$$

(2.27)

Such a measurement will yield a very rough approximation for the number of atoms. Because the lens occupies only a small solid angle, any sort of error in measuring the
diameter or the distance between the MOT and the lens has a great impact upon the final calculated population value. A typical rule of thumb is that the calculation is only precise to an order of magnitude.
Chapter III
Experimental Methods

3.1 Doppler Free-Spectroscopy

Both the absorption imaging and laser cooling techniques rely on the ability to precisely lock the lasers to a desired frequency. If a laser is simply sent through a Rubidium gas cell, the intensity of the laser as a function of frequency will be Doppler broadened as shown in Figure 6. Within each of the peaks are actually several obscured transitions.

Figure 6: Each Doppler broadened peak actually contains three transition lines to particular $F'$ levels, as well as three crossover peaks. However, the thermal motion of the atoms makes it impossible to resolve these transitions using standard methods. [4].

This Doppler broadening can be removed using the process of Doppler-free saturated absorption [7]. The relevant laser beam is split into two beams, one of which will be sent into the MOT either to cool or image the atomic population. The other beam, which is much weaker, will be used to set the frequency of the first beam. This beam is then itself
split into three beams. Two of the beams are relatively weak, with each comprising only four percent of this locking beam’s total power, and are sent through a Rubidium vapor cell. They are then steered into a photo detector. The frequency of the laser beam is then scanned over a range of a few hundred MHz at a rate of about 10 MHz. Examining the intensity of one of the weak beams, Doppler broadened absorption is apparent.

The next step is to remove this Doppler broadened spectrum, which results from the thermal motion of the atom. This is accomplished by sending the third and strongest component of the beam, the pump beam, into the Rubidium cell in the opposite direction of the two weak probe beams. This is shown in Figure 7. The system is constructed so as to allow for maximum spatial overlap between one of the probe beams and the pump beam.

Figure 7: The Doppler-free spectroscopy setup is shown above. The spatial overlap between the pump and one of the probe beams causes a difference in the intensity of the probe beams recorded at the photodetector when the beams are at the resonance frequency [4].
The much more powerful pump beam removes the Doppler saturation by creating a difference in the atomic populations that interact with the probe beams.

There are two effects through which the pump beam alters the population. The more significant is hyperfine pumping. The pump laser excites atoms from the \( F=1 \) to \( F'=1 \) excited state. From quantum selection rules, the excited atom can decay into either the \( F=1 \) or \( F=2 \) ground state. If the atom decays to the \( F=1 \) state, the process will likely repeat itself. With a decay to the \( F=2 \) state, the atom will remain in this state. However, the motion of the atoms in the Rubidium cell prevent a large buildup of \( F=2 \) state atoms in the beam path. The ground state population is also altered through the method of saturation. An excited atom will typically last 28 ns before decaying [8]. A sufficiently intense laser may be able to sustain a significant atomic population in the excited state. The theoretical maximum population change results in fifty percent of the atoms in the excited state and fifty percent in the ground state. However, this requires a very powerful laser, and more typical values are between two and twenty percent [8].

Having discussed how the pump beam changes the population, it is now possible to show how the interaction of the pump and probe beams removes the Doppler broadening [8]. Let us first consider a case where the laser is red-detuned, so that in order for a photon to be absorbed, the relevant atom must be moving towards the photon. The pump and probe beams are traveling through the rubidium cell in opposite directions. Thus the two beams interact with two different sets of atoms. The pump beam does not affect the absorption of the probe beam. Subtracting this probe beam from the other probe beam would yield a null signal. Now consider the case in which the laser is at resonance frequency. The probe and pump beams now interact with the same population of atoms, those that are stationary in the lab frame. Because the probe laser excites many atoms outside of this
population, the absorption of the probe beam is substantially reduced. Subtraction from the other probe beam yields a substantial signal. As we further increase the frequency of the laser, the beam becomes blue-shifted. Only those atoms moving away from the beam with sufficient velocity will be able to absorb the beam. The probe and pump beams are once again interacting with populations of different atomic velocities. The probe beam’s absorption is therefore not affected by the pump beam. Thus, by introducing the interaction between the pump beam and probe beam and using the other probe beam as a control, it is possible to precisely locate the resonance frequency of atomic transitions, as shown in Figure 8. In our case, we are particularly interested in the Rubidium 87 F=2 to F’ transition.

![Rubidium Doppler Free Spectrum](image)

**Figure 8:** The two graphs above show Doppler free spectra. The panel on the left is the entire spectrum for both Rubidium-85 and Rubidium-87. The right panel is the Rubidium-87 F-2 transition. Notice the individual peaks of transitions to particular F’ value.

Beyond the expected atomic transitions, there are cross-over peaks at frequencies midway between two transitions that have the same lower level. These additional peaks occur because there are certain populations of atoms with the correct velocity to interact with both the probe and pump beam, even though they are not stationary. The probe beam stimulates the atoms to one transition, and the pump beam stimulates the atoms to make the other transition.
3.2 Absorption Imaging system:

Shown in Figure 9 is the layout of the absorption imaging system.

The probe laser for the imaging is generated by a New Focus 10mW power laser with a mean wavelength of 780.24 nm. The laser is controlled by a frequency peak lock-box, which locks the laser to a frequency at a desired signal peak. The laser beam then runs through an optical isolator. This component is essential to prevent damage to the laser as reflection off
an optical component can re-enter the laser, causing permanent damage to the lasing components. The isolator prevents such feedback. Upon leaving the isolator, the beam transverses a 1/2 wave plate which, when coupled with a beam splitter, allows us to adjust the fraction of the photon populations in either polarization.

From the beam splitter, we now study the path through the Doppler-free saturated absorption system, which removes the Doppler broadening found in standard absorption spectrums. The beam is reflected off of two mirrors and sent through a glass block. Transmission through the glass occurs at a rate of ninety-six percent with four percent of the beam reflected at each air-glass interface. The remainder of the beam passes through the glass to be redirected and used as the pump beam for the Doppler free saturated spectroscopy. Because of the two reflections, the second reflected beam is four percent weaker than the first beam. The internal electronics of the photodetector, which will detect the two beams and determine the difference between the strengths of the two, requires that the stronger beam be sent into one particular photodiode and the weaker beam be sent into the other. This additional constraint requires the use of the first two mirrors. Before entering the detector, the beams transverse a cylindrical rubidium cell. The pump beam is reflected by two mirrors and sent though the rubidium cell in the opposite direction of the probe beams. The mirrors are placed so as to maximize the volume of interaction between one of the probe beams and the pump beam.

The laser is controlled by the servo-lockbox that initially drives the laser to scan over a range of frequencies. The photodetector’s output is displayed on an oscilloscope revealing the spectrum shown in Figure 8. The lockbox’s frequency range and center frequency can then be manually adjusted to a small range about a peak point and locked there. For the imaging system, we are interested in locking to the peak of Rubidium-87 transition from
$5S_{1/2}\, F=2$ to $5P_{3/2}\, F'=3$. This differs from the locking of the cooling beam, which is red-detuned approximately 10 MHz from the same transition. The pumping transitions are shown below in Figure 10.

Figure 10: The probe beam is tuned for the transition from $5S_{1/2}\, F=2$ to $5P_{3/2}\, F'=3$. The cooling beam is detuned by 10 MHz from the same transition. This ensures that the probe beam is interacting with the cooled atoms. Not shown is the repump beam which keeps atoms from building up in the $5S_{1/2}\, F=1$ “dark” state.

There is also a repump beam to keep atoms from falling into the “dark” state $5S_{1/2}\, F=1$. This occurs because the cooling beam can cause transitions from the $5S_{1/2}\, F=2$ to the $F'=1$ or $F'=2$ states through non-resonance pumping. When these states decay, they may decay to the $5S_{1/2}\, F=1$ state, which is “dark” to the cooling beam. Thus these atoms are no longer cooled. Over time, the Rubidium population is shifted entirely to this state without the repump beam, crippling the experiment. This situation is easily prevented by having a repump beam locked to the $5S_{1/2}\, F=1$ to $F'=2$ transition.
Returning to the absorption imaging system, the fraction of the laser beam not diverted by the beam splitter passes through a computer controlled shutter. The imaging beam can only be allowed to pass through the MOT for a short period of time. This requires use of an acousto-optical modulator (AOM), which acts as a switch, allowing for microsecond control of the imaging beam. If the probe beam were controlled mechanically using a shutter, the exposure time of the beam would be approximately 1ms. Such an exposure would almost assuredly damage the CCD camera as well as dissipate the MOT in the first few microseconds. Thus the level of absorption would be very difficult to detect due to the magnitude of the beam’s intensity. However, the AOM is not a perfect switch and allows some of beam to leak into the MOT, preventing the creation of a healthy atomic population. To prevent this light leakage, a shutter is used.

The acousto-optical modulator (AOM) is of tremendous importance in the imaging system. A brief discussion of the device is included here for the reader’s benefit [9]. An AOM consists of a Piezo-electric transducer attached to a piece of glass. The AOM driver provides an electrical signal that oscillates at radio wave frequencies. This signal drives the transducer, causing it to vibrate and create sound waves that travel through the glass. The longitudinal waves imply a varying index of refraction in the glass component as the density of the glass varies. As the waves travel through the glass, the light is diffracted by the changing density of the glass and Bragg diffraction results.

Unlike standard Bragg diffraction, the density variation in the glass is not stationary. As a result, there is a Doppler shift of the laser beam’s frequency as it interacts with the crystal. The extent of the shift depends on the angle at which the laser beam enters the crystal. It is possible for the light frequency to be shifted by any multiple of the driving
frequency of the AOM. The multiple is defined as a positive or negative integer \( m \). When the beam exits the glass, it does so at an angle \( \theta \) given by

\[
\sin(\theta) = \frac{m\lambda}{2\lambda_{\text{sound}}} \tag{3.1}
\]

where \( \lambda \) is the wavelength of the light. Because the angle at which the beam leaves the AOM depends on the frequency of the Doppler shift, it is possible to use the AOM as a very high speed optical switch. By picking the angle at which the beam enters the glass, which largely determines \( m \), and the frequency of the sound wave, we can exactly pick \( \theta \). Activating the AOM, we can then change the path of the laser with very little delay. In this experiment, the time it takes for the AOM to redirect the laser beam once it receives the signal is only 860 ns. Such time precision is essential for accurate time of flight measurements.

The AOM presented two additional difficulties with which the author was not familiar. First, the AOM’s operation at radio frequencies means that the wavelength of the signal is on the order of a meter or so. Such a wavelength results in a circuit when the size of the system is a few meters. While this is not necessarily a problem when the signal is sent along a single path, if one tries to both drive the AOM head and monitor the signal, the result is an unstable signal that cripples the AOM. The second difficulty stemmed from the voltage needed to set the frequency of the AOM oscillation. This frequency is determined by a Labview program which sends a signal to a National Instruments PXI-6602 counter/timer module. The module then generates the voltage which is input into the driver. However, the AOM used was a NEOS unit centered at 110 MHz. Thus it was necessary to apply a considerable voltage to the AOM to drive the frequency to the 130 MHz needed. Shown in Figure 11 is the AOM frequency as a function of driving voltage.
Figure 11: The frequency output as a function of the input voltage. The AOM used was designed for the frequency of 110 MHz, so it required a considerable signal to reach the desired driving frequency.
It was determined after much effort that the National Instruments module was unable to generate voltages greater than 10 volts. Above this limitation, the module generates negative voltages, rendering the AOM driving frequency worthless. This limitation was overcome by constructing a non-inverting amplifier that tripled the voltage from the National Instruments module. A voltage input of 4 volts generated the 12 volt output that drove the AOM frequency to 133.5 MHz, the exact value needed for the atomic transitions. The amplifier initially made use of high quality op-amps which are well suited for removing noise from an input signal. However, this meant that when our input voltage terminated, the amplifier exhibited classic ringing for several microseconds, requiring the use of a more forgiving op-amp designated OP-27.

Operating the AOM at a frequency so far removed from its designed frequency significantly reduces the efficiency of the AOM, from about 90% to 65% in our case. This may be a result of the decreasing amplitude of the AOM oscillation. The signal’s amplitude from the AOM driver to the AOM head decreased from 26 volts peak to peak to 14 volts peak to peak.

In order to change the angle of the laser as it leaves the AOM, it is also necessary to change the frequency of the light by some multiple of the driving frequency of the AOM, as is apparent from equation 3.1. Thus the probe beam cannot initially be at the frequency necessary for the $5S_{1/2} F=2$ to $5P_{3/2} F'=3$ transition. Instead, the laser is locked to the crossover peak of $F'=2$ and $F'=3$. One can show that these crossover peaks occur midway between the frequency peaks of the two standard transitions. Thus the crossover peak of $F'=2$ and $F'=3$ is 133.6 MHz from the $5P_{3/2} F'=3$ line. If we lock the probe beam to the crossover peak and then have the AOM shift the frequency of the laser by approximately
133.6 MHz, the photons will have sufficient energy to be absorbed by the atoms for the $5S_{1/2} F=2 \rightarrow 5P_{3/2} F'=3$ transition.

Once through the AOM, the beam, now properly shifted to the correct frequency for the atomic transition, is sent into fiber coupling. The fiber coupling was done for two reasons. First, it is vastly more convenient than other methods. The fiber coupling allows easy manipulation of the beam and allows the removal of many mirrors and other optical components that would be necessary for alignment. A second, and in this experiment, a more overriding concern, was the incredibly poor quality of the beam. It took considerable time to confirm that the timing and alignment of the system was correct because the CCD imaging of the laser beam did not appear to at all resemble a Gaussian laser beam. The beam eventually had to be isolated by itself and imaged using the CCD camera. The imaging revealed that the beam was multi-modal, with several different peaks. Such poor quality in the beam necessitated the use of fiber coupling to shape the beam into a usable intensity distribution.

As the beam exits the fiber, it is radiated spherically outward from the point where the fiber terminates. It is necessary to collimate the light using a pair of lens. By picking the focal length and separation between the radiating point and the lenses, it is possible to collimate the beam to any size. In our case, we wanted a collimated beam with approximately a 1.5 cm diameter. Such a large beam would allow the MOT to be completely bathed in the beam, ensuring that the beam hit the MOT, which is not easy to confirm. The lenses used had a focal length of 50mm and about 100mm. The first lens was placed roughly two inches from the termination of the fiber coupling. Slight adjustment of the separation distance allowed for manipulation of the size of the beam.
Once collimated, the beam again passes through a half wave plate and a beam splitter. As before, this is done to adjust the intensity of the beam to allow for optimal exposure on the CCD camera. The beam is now carefully sent through the MOT apparatus using two mirrors. The beam enters the MOT chamber composed of a small, hollow glass rectangle. It passes through the glass chamber and is then focused using a lens. The lens magnifies the MOT, to allow for more accurate measurements of the time of flight and atomic population.

The CCD camera used was an Apogee Alta. The camera was controlled using two software programs. The first was MaxIm DL, an imaging program commonly used in astronomy and adapted for our more terrestrial imaging. The MaxIm DL software provides an excellent system for controlling the camera. The program can be used to control such parameters as the exposure time of the image, the temperature of the CCD, how many images are to be taken, and whether the camera should trigger from an external source. In our case, the labview program used the NI PXI-6602 module to send a five volt signal to the camera. The 5.0 volt signal was reduced to 3.3 volts using a voltage divider. This was necessary to prevent damaging the camera which runs on a LVTTL pulse. The pulse was then allowed to trigger the camera. The Maxim DL software is used to place the camera in external trigger mode, as well as to adjust other factors.

The two most relevant parts of the camera are the camera shutter and the CCD chip. The shutter poses an issue because of its considerable size. The shutter has a one-inch diameter. Such a large shutter was found to require 26 ms to open or close. This time delay must be accounted for within the labview program. In addition, the large vibrations caused by the movement of the shutter introduce a significant amount of variation into any given image. In particular, it was very difficult to precisely remove background noise from the
absorption image due to the differences between the background and absorption shot that is likely caused by the vibration. In retrospect, using two lenses to focus and re-expand the beam while using a smaller shutter located at the point where the beam is at its narrowest would have greatly reduced the vibration. However, time and space on the optical table were both limited. The CCD chip is a KAF-0402ME manufactured by Kodak. It is a relatively small chip with an area of 32mm², necessitating precise alignment of the camera with the magnification system. The quantum efficiency of the chip is 0.35.

Shown below is a picture taken of the apparatus as it neared completion.

Figure 12: In the foreground is the Doppler Free system with the beam splitter clearly visible. In the background, the red wire coil is the MOT and the blue CCD camera can be seen as well. This picture was taken before fiber coupling of the probe beam, which is therefore not shown.
Having now described the spatial construction of the apparatus, we now turn to the temporal settings. Absorption imaging requires exquisite timing. The probe beam impacts the CCD chip for only a few hundredths of a millisecond. Assuring that the AOM, shutters, camera, and MOT system are coordinated is not a trivial task.

As previously discussed, the camera shutter is the crudest component in terms of temporal control. There is a $25 \text{ ms} \pm 1 \text{ ms}$ time delay from when the camera receives a signal to when the camera aperture opens. Thus the camera shutter must be open for a relatively long period of time to avoid the possibility of temporal misalignment. The exposure of the CCD chip is determined within the MaxIM DL program. However, the length of the exposure time could not be set less than $20 \text{ ms}$ by the program. Given the delays in the camera, such an exposure limit seems reasonable.

Shown in Figure 13 is a timing diagram for the system.
Figure 13: The timing cycle begins with a start trigger, which triggers the camera. The CCD chip is exposed at the same time that the probe shutter is opened, and the AOM switch is activated. The MOT cooling beams are blocked and the magnetic field is shut down during this process.

For absorption imaging, it is essential that the cooling beams of the MOT be blocked using a shutter. Fluorescence of the atomic population as the atoms absorb and radiate photons will be captured by the CCD camera and can easily overwhelm the absorption signal. However, the laser is essential in generating the potential that maintains the density. A typical MOT generated by the system used will likely dissipate within five milliseconds of the
blocking of the cooling lasers [4]. Thus it is essential that the cooling shutter be closed just before the picture is taken. This constraint forces relatively precise timing between the camera shutter, cooling shutter, and AOM control.

An effective way to ensure a proper time series was to adjust the time delays of each process while imaging using the CCD camera. The delay on the pulse relative to the camera shutter was adjusted so that an image was obtained in which the shutter was not fully opened when the probe beam pulse was sent. Delay of the pulse was then increased until the shutter no longer impinged upon the pulse. When this image was consistently replicated, the probe pulse and camera shutter were correctly synchronized. We repeated the process using the cooling beam shutter. The camera shutter was opened and an image taken in which fluorescence of the MOT was visible. We then decreased the delay of the cooling beam shutter, until fluorescence was no longer visible. When this was consistently replicated (i.e. twenty consecutive images without fluorescence), the camera and cooling beam shutters were assumed to be correctly aligned.
Figure 14: A typical alignment shot. The camera shutter is opening too late. By the time the shutter is completely open, the AOM switch has closed and the probe beam is no longer impacting the CCD chip, explaining the pattern above.

By adjusting the relative difference between the shut-off of the magnetic field and the closing of the cooling beam shutter, it is possible to introduce some molasses cooling. This can be desirable if lower temperatures are required, but in our case this is of limited value because the cooling lasers are not of sufficient power to make molasses cooling effective. While a shutter is used to block the cooling beams, the repump beam continues to impact the atomic population.
3.3 Fluorescence imaging system

In comparison to absorption imaging, fluorescence imaging is almost trivial. The only component needed beyond the MOT setup is the lens labeled 9 in the setup diagram (Figure 9). Leaving the MOT cooling beams and magnetic field on, we simply expose the CCD chip and record the intensity of fluorescence. The lens captures some fraction of the intensity and focuses the image on the chip. Such a measurement does not require a probe beam nor the attending difficulties, and is therefore an excellent rough measurement. However, the necessary approximations needed to calculate the atomic population can cause an order of magnitude error in the population estimate. Furthermore, because the MOT beams and magnetic field are not disengaged, there is no way to perform a time of flight measurement with fluorescence imaging. Thus, while fluorescence can be used as a confirmation that the absorption imaging is functioning properly, it is of limited utility. As the MOT system is expanded to allow for a BEC and hopefully atom interferometry, absorption imaging will be the only feasible option for recording the interference patterns.
Chapter IV
Experimental Results

4.1 Fluorescence Imaging

Using fluorescence imaging, it is possible to gain an estimate of the number of atoms trapped by the MOT. Shown in Figure 15 is an example of fluorescence imaging. The bright spherical cloud in the center is composed of fluorescing Rubidium atoms.

![Figure 15: The bright spherically shaped cloud is caused by fluorescence of the trapped atoms as the atoms interact with the cooling beams.](image)

Calculation of the number of atoms contained begins by summing the total number of counts by the camera. This value, divided by the quantum efficiency of the camera, yields the total number of photons detected by the CCD chip.
We next calculate the energy of an emitted photon using equation 2.25.

\[
E_{\text{Photon}} = \frac{\hbar \omega}{\lambda} = 2.55 \times 10^{-19} \text{J}
\]  

(4.1)

The power absorbed by the CCD camera can now be easily calculated. We multiply the total number of photons by the power and divide by the length of the exposure, which in this case was .020 seconds. The power was determined to have a value of $1.5 \times 10^{-7}$ W. Inserting this value into equation 2.24, along with $L=.26$ meters and $D=.051$ meters, we obtain

\[
\Phi = 16 \frac{L^2}{D^2} P = 6.4 \times 10^{-5} \text{W}
\]

(4.2)

The final step is to calculate the cross section so that equation 2.27 can be used. Using equation 2.26, with a detuning of 10 MHz and an intensity of $1.5 \text{mW/cm}^2$ and textbook values for the other parameters [6], the cross section is found to be

\[
\sigma = \sigma_0 \frac{1}{1 + \left( \frac{\delta \gamma}{2} \right)^2 + \frac{I}{I_s}} = 7.97 \times 10^{-14} \text{m}^2
\]

(4.3)

Using equation 2.27, we can now solve for the total number of atoms, which yields a value of

\[
N = \frac{\Phi}{6I\sigma} = 8.8 \times 10^6 \text{atoms}
\]

(4.4)

The value is presented here without an attempt to determine the error on this value. Past experience using fluorescence values shows that the typical range of error is an order of magnitude. Thus, this value is purely a check on the absorption measurement, which is much more precise.
4.2 Absorption Imaging

For absorption imaging, we take two images. The first image is taken with the MOT cooling beams and magnetic fields just having been shut down. Thus the cooled atoms will not yet have dispersed and so there should be some absorption of the probe beam by the trapped population. A second image is taken in which the MOT has been shut down for a few seconds, thus there is no trapped population. In both cases the probe beam is sent through the MOT chamber and onto the exposed CCD chip. Shown below are two such shots.

Figure 16: This first image shows the probe beam quite clearly. This image was taken just after the MOT apparatus was shut down, so a trapped population was theoretically present.
Figure 17: This image was taken with no trapped population. There should not be absorption of the probe beam.

Dividing the first image by the second image would yield theoretical pixel values of one if no absorption occurred. Values below one indicate absorption. Shown below is the result of this operation.
Figure 18: The white circle marks the area of interest. The dark center with values less than one indicate absorption. The box relates to Figure 19, which is a cross sectional averaged profile of the image.

The image above strongly indicates absorption. The dark center, with values of .86 to .9 indicates levels of absorption of ten to fourteen percent. The white circle corresponds to the area safely presumed to be an area of absorption imaging. The data within this circle will be used to determine the number and density of the atomic population. The boxed area corresponds to the averaged cross section shown below.
Figure 19: The valley-like profile indicates absorption. It is interesting to note the spikes that occur at the edges of the profile. These are the interference patterns that likely result from reflection of the laser off the glass cell. The red vertical lines indicating the range over which the white circle extends.

While an interference pattern is visible at the extreme edges of the probe beam, we also see a strong absorption signature indicated by the low values in the center of the data.

A rough estimate of the number of trapped atoms can now be made. We take the average ratio of the beam intensity with the trap in operation to the intensity without the trap in operation for the area demarcated by the white circle. The result is

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This corresponds to solving for $I(L)/I(0)$ in equation 2.22 where L is the length of the laser beam’s path through the light. We can determine an average value of L by assuming that the MOT is spherical. If this is the case, the average path length through the sphere is given by

$$\langle L \rangle = \frac{V_{sphere}}{\sigma_{sphere}} = \frac{4}{3} \pi r^3 = \frac{4}{3} r$$  \hspace{2cm} (4.6)$$

The radius of the sphere can be determined by studying the size of the absorption image. The magnification of the system is known, and the size of the chip is known. Thus it is relatively simple to determine the radius, which in our case is 1.81 millimeters. We can now use equation 2.22 to solve for the density of the MOT, where we substitute L for x, and use the logarithm of our intensity ratio. The cross sectional value for resonant light is $290.7 \times 10^{-15}$ m². Therefore, the only unknown value is the density n.

$$n = \frac{\ln \left( \frac{I(L)}{I(0)} \right)}{L \sigma} = 1.84 \times 10^{14} \text{atoms} / \text{m}^3$$  \hspace{2cm} (4.7)$$

It is now simple to multiply by the volume of the atomic cloud to determine the number of atoms. The result is

$$N = nV = \left( \frac{4}{3} \pi r^3 \right) n = 4.6 \times 10^6 \text{atoms}$$  \hspace{2cm} (4.8)$$

Determining an error bar on this value is quite difficult. The approximations made undoubtedly have some impact on our value, but they are not particularly severe. The most
significant approximation is likely the choice to use the average absorption ratio rather than attempt a more complicated analysis. However, a review of the intensity profile shows that the absorption ratio is relatively constant as a function of position. Much more likely to be a major source of error are the unforeseen variables in a laboratory that can influence the apparatus. For example, vibrations from a vacuum pump can effect the frequency locking. The apparatus was initially built on a raised platform above an optics table. This raised platform was found to be somewhat unstable and, while this configuration was later corrected, it was shown that the absorption ratio was affected by leaning on the optical table. To account for these errors, the best approach would likely be to take many images and repeat the analysis above. Data points that are clear outliers can be excluded. From the remaining data, it should be possible to construct a Gaussian distribution with corresponding estimations of the standard deviations as estimations of error. As more is learned about the system and how it operates, it is hoped that the operators will become more effective at managing the system’s idiosyncrasies, allowing for consistent measurement.

It is encouraging that the values obtained for the absorption and fluorescence imaging are in agreement. Although they differ by a factor of two, the vagaries of fluorescence imaging are such that absorption and fluorescence imaging are within the errors of the fluorescence value.
Chapter V
Conclusion

5.1 Summary

The absorption and fluorescence imaging systems demonstrated rough agreement in terms of the number of atoms trapped by the MOT. The fluorescence system measured a trapped atomic population of $8.8 \times 10^6$ atoms, while the more accurate absorption system indicates a trapped population of $4.6 \times 10^6$ atoms. However, due to the very large imprecision in the fluorescence imaging values, these values are considered to be in agreement with one another, indicating that the imaging systems were functioning. The absorption system is currently ready for TOF shots, which are scheduled for the coming months.

5.2 Future Efforts

Future work will be focused first on performing a time of flight measurement for the MOT and determining the precision of the absorption imaging system. Also, the NRL group has recently begun construction on a novel “magnetic ring” MOT in which the anti-helmholtz currents are replaced by ring magnets. The absorption imaging system will be used to characterize this new MOT design. In addition, the group is undertaking construction of BEC system. The absorption imaging will be used to study the BEC and also the interference patterns from the atomic interferometry experiments that are planned in the coming years.
Acknowledgements

I would like to thank Professor Frank Moscatelli for his guidance, Jinwei Wu for teaching me the art of experimental physics, and Eun Oh for his help and hospitality. I would also like to thank Eric Duchon for his great set of wheels. My parents, Christine and Bill Forman, and Jayne Koellhoffer deserve thanks for their moral support. Lastly, I would like to thank the Swarthmore College Department of Physics and Astronomy.
References


