2D and 3D Magneto-Optical Trapping of $^{87}\text{Rb}$ in an Atom Chip Bose-Einstein Condensation Apparatus

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2D and 3D Magneto-Optical Trapping of $^{87}\text{Rb}$ in an Atom Chip Bose-Einstein Condensation Apparatus

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2D and 3D Magneto-Optical Trapping of $^{87}\text{Rb}$ in an Atom Chip Bose-Einstein Condensation Apparatus

An Honors Thesis
Presented to the Department of Physics and Astronomy
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in partial fulfillment of the requirements for the
Degree of Bachelor of Science
by
Michał Ćwik
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Introduction

One of the fundamental pillars of scientific exploration is the desire to understand extremes. From the farthest reaches of outer space, to cutting-edge research laboratories; battling on the front lines of science has always been an effort in pushing further and further away from our daily experience. Physics gives us the tools to examine, categorize, and expand upon these sorts of regimes. Bose-Einstein condensation (BEC) is a stunning example of the pursuit of extremes. A BEC is a macroscopic atomic system, characterized by a population of atoms all occupying the same quantum state. Such a system can only exist at the coldest temperatures ($10^{-9} \text{ K}$) and lowest pressures ($10^{-12} \text{ Torr}$) in the universe.

Not long after WW1, an Indian theoretical physicist laid the foundation for the theory now used to describe the statistics of quantum systems. In his article, entitled “Planck’s Law and the Hypothesis of Light Quanta,” Satyendra Nath Bose gave his take on the Maxwell-Boltzmann distribution. His novel statistical interpretation of the thermodynamics of microscopic particles, which didn’t reference classical physics, caught the attention of Einstein. After reading Bose’s work, Einstein generalized it to describe identical particles with discrete energies. In his extension of Bose’s work, Einstein predicted that at a certain critical temperature near absolute zero, a phase transition would occur, creating what we now know as a Bose-Einstein condensate (BEC) [1]. Perhaps unbeknownst to them, Bose and Einstein began a theoretical and experimental revolution in physics, even before Schrödinger had derived his famous equation.

70 years later, a group lead by Eric Cornell and Carl Wieman produced the first BEC in a dilute vapor of rubidium-87 cooled to 170 nanokelvin [2]. Soon afterward, Wolfgang Ketterle and colleagues at MIT achieved BEC of sodium atoms [3]. These accomplishments, recognized by the 2001 Nobel Prize in physics, were only possible after decades of innovation in laser and atomic physics. The 1970s and 80s saw a revolution of cold atom technologies, with the first evidence of laser cooled atoms presented by a group lead by Steven Chu and Arthur Ashkin in 1985 [4]. The next major milestone was the introduction of a means to simultaneously cool and
confine atoms: the magneto optical trap (MOT). Introduced by David E. Pritchard and Steven Chu in 1987, the MOT marked one of the most significant steps forward towards reaching BEC, which was achieved only 8 years later.

In this thesis, I present a comprehensive account of the experimental procedure involved in achieving 2D and 3D magneto-optical traps in an atom chip apparatus, as well as the transition from a “passive” 3D MOT to the “flux-nourished” regime. Before starting my work, the existing apparatus consisted of a primary optomechanical architecture, newly refurbished ColdQuanta RuBECi® with custom atom chip, and ColdQuanta quadrupole coil assembly. The experiment had no optical connection to the lab’s existing frequency-locked laser cooling source. Having laid dormant for over 3 years, the state of every aspect of the apparatus was uncertain, including the condition of the vacuum, the efficacy of the rubidium source, the alignment of all the optical pathways, and the adjustment of the critical MOT waveplates. Before beginning to search for a MOT, we were left with the task of verifying each of these parameters; which involved establishing two new optical fiber pathways, realigning each laser cooling pathway, checking beam quality and dimensions, confirming the helicity of waveplates, and so on. I demonstrate 1) the critical conditions necessary for magneto-optical trapping in a miniaturized apparatus, 2) a procedure to reach the correct alignment, polarization, helicity, and magnetic field configuration needed for 2D+ and 3D MOTs, and 3) the effect of various crucial parameter variations on calibrated atom number, derived from experimentally obtained measurements of 3D MOT behavior.

First, it is essential to introduce the fundamental concepts that govern these phenomena. The theoretical origins of Bose-Einstein condensation are presented using the statistical mechanics approach. We then delve into the experimental tools used to achieve BEC. Light is discussed in the framework of electromagnetism, with special attention paid to polarization. Next, the primary functional concepts of laser cooling, optical molasses, and magneto-optical trapping are described. Finally, the remaining steps toward BEC, falling out of the scope of the work done in this thesis, are summarized.
CHAPTER 1

Theoretical Foundations of Bose-Einstein Condensation

The main focus of this thesis is the magneto-optical trapping of $^{87}$Rb, however, the work done here is simply a stepping stone towards the greater goal of Bose-Einstein condensation. Thus, to refrain from introducing the subject would be a disservice to the reader. In this section, the concept of Bose-Einstein condensation is developed from statistical mechanics, and follows the work of [5, 6, 7, 8]. For a rigorous treatment of the subject, the reader is directed to [1].

1. Bosons, Fermions, and the Pauli Exclusion Principle

In nature, there exists two fundamental types of particles: bosons and fermions. These two general classifications establish the rules by which all of the common types of matter behave. Bosons are particles with integer spin and symmetric wavefunctions. Fermions are particles with half-odd integer spin and asymmetric wavefunctions. Bosons are described by Bose-Einstein statistics, and as such, have unique qualities. Specifically, bosons do not obey the Pauli exclusion principle, a rule describing the allowable quantum state occupation of particles. This means that an arbitrary amount of photons, for example, can occupy the same quantum state. In contrast, two fermions cannot occupy the same state. Predicted over 80 years ago, Bose-Einstein statistics alludes to the existence of a unique phase transition that occurs when a collection of bosons reaches a critical phase-space density. This rapid occupation of the ground state is what we call Bose-Einstein condensation.

The distinction between bosons and fermions applies to fundamental particles like photons, gluons, neutrons, etc. It also applies to more complicated particles, like atoms. The atomic species used in this thesis, rubidium-87, exhibits properties of a boson while being composed of both bosons and fermions. This type of particle is called a composite particle, and can only act like a boson because it contains an even number of fermions, resulting in overall integer spin.
2. Bose-Einstein Condensation

In this section, we explore how Bose-Einstein condensation (BEC) arises from statistical mechanics and quantum statistics. Before deriving important quantities like transition temperature and condensate fraction, it is helpful to conceptualize the phenomenon of BEC in terms of the wave-like nature of matter. A critical concept in quantum mechanics; the de Broglie wavelength of massive particles:

\[ \lambda_{dB} = \frac{h}{mv}, \]  

relates their momentum to Planck’s constant \( h \), where \( m \) is the mass of the particle and \( v \) is its velocity. This idea, introduced by Louis de Broglie in the early 20th century, revolutionized our understanding of the behavior of matter. In this thesis, we consider atoms in a continuum of regimes from thermal (ideal gas) to Bose-Einstein condensed. The thermal de Broglie wavelength

\[ \lambda_{dB} = \frac{h}{\sqrt{2\pi mk_BT}}, \]  

describes the delocalization of atoms. For macroscopic objects at normal temperatures in our daily lives, this quantity is exceedingly small, meaning that the measurement of the position of said objects can be made with great certainty. As the temperature and associated momentum of matter decreases, the uncertainty in position grows to a point where individual particles cannot be distinguished from one another. This is the point at which quantum effects start to dominate the behavior of matter.

To begin our exploration of these quantum effects, let us consider a system characterized by one single-particle state, with \( n \) particles occupying the state, and each particle carrying energy \( \epsilon \). The energy of the state, then, is \( n\epsilon \). We can say that the probability of \( n \) particles occupying the state is

\[ P(n) = \frac{1}{\mathcal{Z}} e^{-n(\epsilon - \mu)/kT}, \]  

where \( k \) is the Boltzmann constant, \( \mu \) is the chemical potential, and \( \mathcal{Z} \) is the grand partition function; the sum of all the Gibbs factors for all \( n \). Unlike fermions, in the case of bosons, \( n \) can be any positive integer. Evaluating the sum, we find that
2. BOSE-EINSTEIN CONDENSATION

\[ Z = 1 + e^{-(\epsilon - \mu)/kT} + e^{-2(\epsilon - \mu)/kT} + \cdots \]

\[ = 1 + e^{-(\epsilon - \mu)/kT} + \left(e^{-(\epsilon - \mu)/kT}\right)^2 + \cdots \]

\[ = \frac{1}{1 - e^{-(\epsilon - \mu)/kT}}. \]

To find the average number of particles in each state, the sum of Equation 1.4 is taken over all positive \( n \):

\[ \bar{n} = \sum_n nP(n) = 0 \cdot P(0) + 1 \cdot P(1) + 2 \cdot P(2) + \ldots, \]

and evaluates to the aptly-named Bose-Einstein distribution:

\[ \bar{n}_{BE} = \frac{1}{e^{(\epsilon - \mu)/kT} - 1}. \]

Figure 1.1. From [9]. A graphical comparison of the Maxwell-Boltzmann, Bose-Einstein, and Fermi-Dirac distributions.

This function describes the average occupancy of a given state in a system of bosons. Figure 1.1 compares the average state occupation number for the Bose-Einstein distribution to the Fermi-Dirac and Maxwell-Boltzmann distributions. As energy decreases, the average occupation of a particular state begins to increase for each distribution. Fermions, following the Pauli exclusion
principle, approach an average single state occupation of one particle as \( \epsilon \to 0 \). Conversely, the number of bosons in the ground state approaches infinity in the low temperature limit where

\[
N_0 = \lim_{T \to 0} \frac{1}{e^{(\epsilon_0 - \mu)/kT} - 1}.
\]  

(1.7)

An infinite number of particles in any circumstance is clearly a nonphysical result. Thus, as temperature decreases, bosons accumulate in the ground state, and the occupancy instead approaches \( N_0 \). The system is described by \( N = N_0 + N_e \), where \( N_0 \) is the occupation of the ground state, and \( N_e \) is the occupation of particles in excited states (where \( \epsilon > \epsilon_0 \)). The number of particles in excited states is given by

\[
N_e = \sum_s \bar{n}_{BE} = \sum_s \frac{1}{z^{-1}e^{\epsilon_s/kT} - 1},
\]  

(1.8)

where \( z = e^{\mu/kT} \) is known as the fugacity of the gas. The integral form of Equation 1.8 can be found by summing over the average occupation numbers of all states:

\[
N_e = \int_0^{\infty} f(\epsilon) \frac{1}{e^{(\epsilon - \mu)/k_B T} - 1} d\epsilon.
\]  

(1.9)

The number of single particle states per unit energy, called the energy density of states, is given by

\[
f(\epsilon) = \frac{2}{\sqrt{\pi}} \left( \frac{2\pi m}{\hbar^2} \right)^{3/2} V \sqrt{\epsilon},
\]  

where \( m \) is the mass of a particle confined in a volume \( V \). When energy approaches zero, \( f(\epsilon) \) also approaches zero. Under the assumption of a typical thermodynamic system, the number of particles in the ground state is negligible, which is a problem for us. For BEC, a large number of particles in ground state is our main concern! To account for this, we subtract the contribution of the ground state before integrating to find \( N_e \). Considering the case where \( \mu = 0 \), we have that

\[
N = \frac{2}{\sqrt{\pi}} \left( \frac{2\pi m}{\hbar^2} \right)^{3/2} V \int_0^{\infty} \frac{\sqrt{\epsilon}}{e^{\epsilon/k_B T} - 1} d\epsilon.
\]  

(1.11)
Utilizing the change of variables $x = \epsilon/kt$, a numerical solution can be found:

$$
N_e = 2.612 \left(\frac{2\pi mkT}{\hbar^2}\right)^{3/2} V. \quad (1.12)
$$

This is the condition under which the excited states have reached their maximum thermal capacity, meaning they will accept occupation from no further particles. Any additional particles not already occupying excited states will then be forced into the ground state. A phase transition occurs as atoms in the excited state $N_e$ have reached their occupation limit and begin to flood into the ground state $N_0$. This sudden collapse into the ground state is known as Bose-Einstein condensation. Above a critical temperature, $T_c$, the chemical potential $\mu$ is negative and nearly all of the atoms are in the excited state, and thus in the thermal phase. Below $T_c$, the number of atoms in excited states is given by

$$
N_e = N \left(\frac{T}{T_c}\right)^{3/2}, \quad (1.13)
$$

meaning the number of atoms in the ground state as a fraction of the total atoms in the system, called the condensate fraction, is

$$
\frac{N_0}{N} = 1 - \left(\frac{T}{T_c}\right)^{3/2}. \quad (1.14)
$$

![Figure 1.2. From [8]. Population of the ground state (blue) and excited state (red) as a function of temperature.](image)
However, BEC occurs in 3D harmonic traps, which have no volumetric parameter, therefore making $T_c$ dependent on the trap frequency, $w_0$, as such:

$$N \approx \left( \frac{k_B T_c}{\hbar \omega_0} \right)^3,$$

and have the corresponding condensate fraction:

$$\frac{N_0}{N} = 1 - \left( \frac{T}{T_c} \right)^3.$$
CHAPTER 2

Experimental Realization of BEC

Before exploring the experimental progress made over the course of this project, it is necessary to describe in a measure of detail the multitude of phenomena that harmonize to create a magneto-optical trap. Starting with light, the primary building block of a MOT, we see how atoms can be cooled by the process of absorption and spontaneous emission of light. The concept is then extended by considering how the influence of an external magnetic field permits the simultaneous cooling and trapping of atoms. Finally, the remaining steps toward BEC are summarized.

1. Light and Polarization

For reasons that will become clear in the following sections, a treatment of light as an electromagnetic wave and the concept of polarization is required to introduce the laser cooling and magneto-optical trapping techniques, which are fundamental to the experimental process of this project. The following introduction is assembled from [6, 10, 11].

According to Maxwell’s equations, light is an electromagnetic wave, comprised of orthogonal electric and magnetic fields that oscillate in amplitude and propagate together in a transverse fashion at the speed of light. By convention, the orientation of the electric field with respect to the direction of propagation is known as the polarization. To investigate polarization, we first consider an electromagnetic wave propagating in the \( z \) direction:

\[
E = E_{0x} e^{i(kz−ωt+δ_x)} \hat{x} + E_{0y} e^{i(kz−ωt+δ_y)} \hat{y},
\]

(2.1)

where \( k \) is the wave vector, \( ω \) is the angular frequency, and \( δ = (δ_y − δ_x) \) is the phase difference. By considering their complex amplitudes, we can express the \( x \) and \( y \) components of the electric field as a vector, called the Jones Vector:
\[ \mathbf{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_0 e^{i \delta_x} \\ E_0 e^{i \delta_y} \end{bmatrix}. \]  

(2.2)

In propagating a distance corresponding to a wavelength \( \lambda = c/f \), the electric field vector rotates elliptically if viewed along the axis of propagation. If either component of the electric field vector has zero amplitude, then the light is considered to be linearly polarized along the direction of the opposite component. This is a special case of elliptical polarization that occurs when \( \delta = 0 \) or \( \delta = \pi \). By convention, linear polarization in the \( x \) direction is called horizontal, and linear polarization in the \( y \) direction is called vertical. The Jones vectors for these states are:

\[ \mathbf{E}_{\text{LHP}} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad \mathbf{E}_{\text{LVP}} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \]  

(2.3)

Another special case is when \( \delta = \pm \pi/2 \). The electric field vector now travels in a helical pattern, drawing out a circle if viewed head-on. This is circular polarization. The direction of rotation of the electric field vector determines the left/right handedness or \textit{helicity} of the circularly polarized light. The thumb points in the direction of propagation, and the fingers curl in the direction of rotation of the electric field vector. The corresponding Jones vectors are given by:

\[ \mathbf{E}_{\text{RCP}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix}, \quad \mathbf{E}_{\text{LCP}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}. \]  

(2.4)

However, light from typical sources such as the sun or incandescent light bulbs is a superposition of many polarization states, and is therefore considered to be \textit{unpolarized}. A linear polarizer is an optical system that transforms a wave to linear polarization. In the language of the Jones calculus, such an optical system is a particular example of the matrix operator \( \mathbf{T} \), where the input and output waves are given by \( \mathbf{E}_1 \) and \( \mathbf{E}_2 \), respectively:

\[ \mathbf{E}_2 = \mathbf{T} \mathbf{E}_1 \]

\[ \begin{bmatrix} E_{2x} \\ E_{2y} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} E_{1x} \\ E_{1y} \end{bmatrix}. \]  

(2.5)
1. LIGHT AND POLARIZATION

To convert some input light $\mathbf{E}_1$ to linear polarization, the following Jones matrices are used:

\[
\mathbf{T}_{\text{LHP}} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{T}_{\text{LHP}} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}.
\] (2.6)

Another type of Jones operator is the wave retarder or waveplate. This delays a component in the Jones vector by a specific phase such that one polarization state is converted to another. In a laboratory setting, the task of the Jones matrix is performed by exploiting the birefringent properties of crystal, such as quartz. The three main polarization optics used in this project are the $\lambda/2$ waveplate, the $\lambda/4$ waveplate, and the polarizing beamsplitter (PBS). The $\lambda/4$ waveplate is particularly relevant to cold atom physics because it converts linear polarization to circular polarization, which is involved in magneto-optical trapping. For example, consider a $\lambda/4$ waveplate with vertical fast axis. Incident light with linear polarization of 45° with respect to the axis would be converted to right-handed circularly polarized light as such:

\[
\begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix}_{\lambda/4} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}_{45^\circ} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}_{\text{RCP}}.
\] (2.7)

To direct light in an apparatus, a polarizing beam splitter (PBS) is a device that disseminates between horizontal and vertical polarization states, allowing one to pass through, and reflecting the other by 90°. By first shining light through a $\lambda/2$ waveplate mounted to a rotational stage, a PBS can act as a continuously variable laser power splitter. In summary, $\lambda/4$ waveplates convert linearly polarized light to circularly polarized light, and vice versa. $\lambda/2$ waveplates rotate linearly polarized light by 45°, and flip helicity of circularly polarized light.

For magneto-optical trapping, determining the helicity of light is of significant importance. To find the $\lambda/4$ waveplate orientation that coincides with right or left-circularly polarized light, a device called a polarization analyzer is used. The analyzer consists of a $\lambda/4$ waveplate that has been calibrated such that incident (right handed or left handed) circularly polarized light is converted to (horizontal or vertical) linear polarization. The light then passes through a PBS which indicates the helicity of the input light. The specific state of handedness is not important for our purposes, just the distinction between the two.
2. Laser Cooling

The goal of many atomic physicists is to study the behavior of matter on the molecular, atomic, and subatomic levels. However, there are only so many observations that can be made in the four classical phases of matter. In order to study quantum mechanical behavior, specifically BEC, we must remove the thermal ‘noise’ that is inherent in the movement of atoms at room temperature. In practice, this can be achieved by decreasing the temperature of the atoms; thereby stripping them of their kinetic energy. To reach $T < T_c$, no classical refrigeration techniques are nearly sufficient. BEC requires an environment so cold that any stray thermal atoms would have so much energy comparatively that they could completely destroy an ultracold sample. To cool atoms down without physically interacting with them, physicists use light. This technique, called Doppler cooling, functions based on the principle of absorption and spontaneous emission. When a counterpropagating photon of the correct resonant frequency is absorbed by an atom, it delivers a “momentum kick” equivalent to $\hbar k$. Then, the atom spontaneously emits another photon in a random direction. Over many absorption/emission cycles, the net momentum imparted on the atom from random emission averages out to zero. The overall effect of these series of momentum kicks is to reduce the velocity, and thus the temperature, of the atom. Extending this process to a collection of atoms allows many of them to be cooled simultaneously. Considering that the momentum of an atom being cooled is $\sim 10^3$ times that of a photon, the process is akin to slowing a speeding bowling ball with a stream of ping pong balls [12]. Luckily, lasers can fire $\sim$-quadrillions of photons per second, meaning that not only can low temperatures be reached, they can be reached very quickly. This section is compiled from [13, 6].

2.1. The Scattering Force. Light can slow down atoms because radiation carries momentum. By conservation of energy, when radiation is absorbed by an atom, it will experience a corresponding change in it’s momentum. The force radiation exerts on a given area $A$ is given by

$$F_{\text{rad}} = \frac{IA}{c}$$

(2.8)

where $I$ is the radiation intensity and $c$ is the speed of light. Lasers are used to deliver this pressure because they produce light that is highly collimated and monochromatic. This is
important because the energy levels of atoms are quantized, meaning they will only absorb light of a narrow range of frequencies. A laser beam, counterpropagating with respect to the atom, will exert a force $F = -\sigma_{\text{abs}} I/c$, where

$$\sigma(\omega_0) = 3 \times \frac{\lambda_0^2}{2\pi} \simeq \frac{\lambda_0^2}{2} \quad (2.9)$$

The absorption cross section, $\sigma$, represents the probability of absorption of incident radiation. Laser cooling is so effective because the absorption cross section for on-resonance atoms is multiple orders of magnitude larger than the physical size of the atom.

The spontaneous emission of photons in random directions after each momentum kick, called scattering, produces a net force in the opposite direction of propagation, called the scattering force:

$$F_{\text{scatt}} = (\text{photon momentum}) \times (\text{scattering rate})$$

$$= \hbar k \frac{\Gamma}{2} \frac{I/I_{\text{sat}}}{1 + I/I_{\text{sat}} + 4\delta^2/\Gamma^2}. \quad (2.10)$$

The rate at which photons are scattered is

$$R_{\text{scatt}} = \frac{\Gamma}{2} \frac{I/I_{\text{sat}}}{1 + I/I_{\text{sat}} + 4\delta^2/\Gamma^2}. \quad (2.11)$$

where $\Gamma$ is the natural linewidth of the atomic transition, and $I/I_{\text{sat}}$ is the relationship between the laser intensity and a factor based on the atomic state and the polarization of the light. The laser detuning the from atomic resonance frequency $\omega_0$ is given by:

$$\delta = (\omega - \omega_0 \pm kv), \quad (2.12)$$

where $\omega$ is the frequency of the laser, detuned to compensate for the Doppler shift of the atoms travelling at velocity $v$ relative to the photons. This is exactly the parameter we exploit in the lab to cool atoms.
2.2. Optical Molasses. To see how we can employ the scattering force to cool atoms, we must consider the one dimensional case. Many people have experienced how the frequency of an ambulance siren is shifted in the frame of the observer to be higher when it drives toward someone, and lower when driving away. The same is true photons propagating towards atoms. Doppler cooling exploits this effect by detuning the laser frequency to the red of the resonance frequency, such that the counterpropagating atom ‘sees’ the incoming photons as properly tuned to resonance, thereby absorbing them. Figure 2.1 depicts this process in the one dimensional case. The result is an overall force that slows the atom down. It can be expressed, assuming $kv << \Gamma$, as the difference in the scattering force exerted by laser 1 and laser 2:

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

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

\[
\simeq -2\frac{\partial F}{\partial \omega} kv
\]

\[
\simeq -\alpha v.
\]

$F_{\text{molasses}}$ is thus a frictional force imparted by counterpropagating laser beams that resists the motion of atoms, akin to a particle moving in a viscous fluid, like honey or molasses. The technique was first implemented by Steven Chu and Arthur Ashkin in 1985 [4]. Chu was a partial recipient of the Nobel Prize in 1997 for this work.

This premise can easily be extended to three dimensions by adding cooling beams along the other two orthogonal axes. However, due to the nature of photon scattering, this technique cannot be used to cool atoms to arbitrarily low temperatures. Although the effect of many spontaneous emission events averages out to zero, each event still imparts a recoil velocity $v_r = \frac{\hbar k}{m}$ on the atom. These momentum kicks cause the atom to randomly ‘walk’ in momentum space. Thus, as the temperature of the atoms decreases, they will inevitably be prevented from being slowed any further. This temperature, given by

\[
T_D = \frac{\hbar \Gamma}{2k_B}
\]

is the Doppler cooling limit. This is the lowest achievable temperature for two-level atoms in an optical molasses. In reality, atoms have far more complicated energy level configurations. In
3. Rubidium 87

The first atomic species to be successfully laser cooled, trapped, and Bose Einstein condensed were all among the alkali metals. Atoms from this group in the periodic table have a ground state...
state with a closed shell with one valence electron. In order for light to exert the scattering force on an atom, it must excite the valence electron to the $p$-orbital of the atom. The frequency of light needed to drive this transition is dictated by the fine and hyperfine energy structures of the particular atomic isotope. In the case of rubidium-87, as with other alkali metals, light of this frequency ($\omega_0 = 2\pi \times 384$ THz $\rightarrow \lambda \sim 780$ nm) is within the visual spectrum, meaning that the lasers needed to produce it are cheap and readily available. The fine structure arises from the coupling between the orbital angular momentum of the outer electron and its spin angular momentum. The total electron angular momentum interacts with the total nuclear angular momentum to produce the hyperfine structure, as depicted in Figure 2.2. The particular atomic transitions allowed within the hyperfine structure are governed by a set of selection rules:

$$\Delta F = 0, \pm 1 \quad \text{and} \quad \Delta m_F = 0, \pm 1.$$  \hspace{1cm} (2.15)

The specific transition used for laser cooling in $^{87}$Rb is given by the the D$_2$ line ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$). This transition is a nearly closed optical loop. This means that by detuning to below the $(F = 2) \rightarrow (F' = 3)$ transition, $^{87}$Rb can be driven cyclically. The loop is nearly closed because some $(F = 2) \rightarrow (F' = 2)$ transitions will inevitably happen. Atoms in the $(F' = 2)$ state can then decay to the $(F = 1)$ state, called the ‘dark state.’ Due to the selection rules, atoms in this dark state cannot re-enter the cooling loop without the help of separate light on resonance with the $(F = 1) \rightarrow (F' = 2)$ transition, ‘repumping’ the atoms back into the cycle.

4. Magneto-Optical Trapping

The Doppler cooling technique only creates a velocity-dependent force. In an optical molassas, atoms are slowed, but will eventually, over the course of many scattering interactions in different directions, escape the area of light-influence. To create a trap, a position-dependent force is required. The solution was to introduce a magnetic field gradient, which, in harmony with the light field, elicits confinement. Today, magneto-optical trapping is used for many different types of experiments in labs around the world. However, before the MOT was conceived, many in the physics community believed that optical confinement wasn’t possible.

4.1. The Earnshaw Fallacy. In the early 1980s, an “Optical Earnshaw Theorem,” analogous to Earnshaw’s theorem in electrostatics, was proposed with the claim that it was impossible
to create a atomic trap using the scattering force of light [16]. Arthur Ashkin and James Gordon came to this conclusion using the following proof [17]:

The scattering force of light can be thought of as

\[
\vec{F}_{\text{scatt}} = c \vec{S}
\]  

(2.16)
where $c$ is a constant of proportionality and $\vec{S}$ is the Poynting vector. One of the continuity equations from electromagnetic theory states that

$$\frac{\partial u}{\partial t} + \nabla \cdot \vec{S} = 0$$

(2.17)

where the first term is the change in energy density per unit time and the second term is the divergence of the Poynting vector. Herein lies the proof: to create a trap, you need an inwardly confining force, meaning that

$$\nabla \cdot \vec{F}_{\text{scatt}} < 0,$$

(2.18)

but if the laser beams used to create the molasses are in steady state, i.e. the energy density is constant over time, then the first term in Equation 2.17 is 0, meaning that the divergence of the Poynting vector must also be 0. If this is the case, then by Equation 2.16,

$$\nabla \cdot \vec{F}_{\text{scatt}} = 0.$$

(2.19)

By most measures this seemed to prove that creating a trap that exploited the scattering force of light was impossible. However, one of David Pritchard’s students ended up showing that this was not necessarily the case [18]. After a lecture discussing the aforementioned proof, the student approached Pritchard and asked him to explain why it was the case that light could not trap atoms. During his explanation, Pritchard had the staggering idea that would end up setting the groundwork for all cold atom research going forward. He determined that one of the main assumptions in the proof was incorrect; that the constant of proportionality, $c$, in the scattering force was just that: constant. This incorrectly inferred that atoms in the molasses light field were simple two-level atoms. Pritchard correctly pointed out that laser coolable atoms like rubidium have spin, and thus a complex hyperfine structure, meaning that the scattering force was also dependent on both the polarization of the cooling light and the magnitude and direction of any surrounding magnetic field. By carefully varying these parameters, he realized that it was in fact possible to trap atoms using the scattering force, and so the magneto-optical trap was born.
4. MAGNETO-OPTICAL TRAPPING

4.2. The One Dimensional Case. The conventional magneto-optical trap uses 6 counter-propagating beams of light, 2 each along each of the three principle axes. It also requires a uniform magnetic field gradient, which is created by a pair of coils in anti-Helmholtz configuration, meaning that the current in each coil is flowing in opposite directions with respect to each other. A common misconception is that the magnetic field is providing the confining force within a MOT. This statement obscures the mechanism operating on the atomic scale. The true role of the anisotropic magnetic field is to exploit the Zeeman effect. This effect describes the splitting of atomic energy levels subject to a weak external magnetic field. For atoms to be confined under the influence of the Zeeman effect, they require circularly polarized light. Photons that are circularly polarized drive the correct hyperfine transitions in rubidium that allow it to be Doppler cooled in a position-dependent manner.

To get a grasp of how a system of such multifaceted complexity operates, it is helpful to reduce a MOT to the one dimensional case. Consider an atom traveling along the $z$ axis with total angular momentum $J$, and Zeeman-split sublevels $M_e = \pm 1$. Limiting the system to the
4. MAGNETO-OPTICAL TRAPPING

Figure 2.4. Diagram from [19]: Visualization of Zeeman sublevel splitting in a MOT configuration. Axis denoted as “Position” points in the $+\hat{z}$ direction. Atoms located in the $+z$ region experience stronger scattering forces from the $\sigma^-$ beam than the $\sigma^+$ beam, and vice versa for atoms in the $-z$ region.

$J_g = 0 \rightarrow J_e = 1$ transition of the atom, the quantization axis is then defined as $|J, M_z\rangle$. The energy level shift experienced by the atom in external field $B_{\text{ext}}$ is given by the Zeeman energy

$$\Delta E_z = \mu_B g_J m_J B_{\text{ext}},$$  \hspace{1cm} (2.20)

where $\mu_B$ is the Bohr magneton and $g_J$ is the Landé g-factor [20]. In a typical MOT, the coil configuration creates a quadrupole field. Towards the center of the trap, the field gradient can be approximated as constant, meaning the energy level splitting will take on the form

$$\Delta E_z = \mu_B g_J m_J \frac{\partial B}{\partial z}.$$  \hspace{1cm} (2.21)

From this, we can see that the energy level splitting increases linearly with increasing $|B_{\text{ext}}|$.  

Using Figure 2.4 as a visual guide, let us explore the behavior of an atom in a MOT. If the atom is traveling in the $+\hat{z}$ direction, the electric field of the counterpropagating right circularly polarized laser beam will drive the bound electron of the atom in the same sense as the field, imparting angular momentum $-\hbar$, thus driving a $\sigma^-$ transition ($|0, 0\rangle \rightarrow |1, -1\rangle$). The beam propagating with the atom, travelling in the $+\hat{z}$ direction, is also right circularly polarized, but since it is propagating — as opposed to counterpropagating — with respect to the atom, it will
drive a $\sigma^+$ transition. In the $z = z'$ position, the magnetic field is positive with respect to the atom’s frame. Therefore, the Zeeman splitting is such that $E_{0,-1} < 0 < E_{0,+1}$, meaning the $M_e = -1$ sublevel is closer to resonance with the redshifted laser light than the $M_e = +1$ sublevel. In this position, the atom will scatter more photons from the counterpropagating light driving $\sigma^-$ transitions, than the light propagating from behind driving $\sigma^+$ transitions which are farther away from resonance, forcing the atom towards the center of the trap. The same principles holds when the atom travels in the $-\hat{z}$ direction.

Extending this concept to three dimensions is as simple as adding two more pairs of counterpropagating beams along the $x$ and $y$ axes. By incorporating the spatially-varying Zeeman shift with the velocity-dependent doppler shift in Equation 2.13, the force becomes:

$$F_{\text{MOT}} = F_{\text{scatt}}^{\sigma^+} (\omega - kv - (\omega_0 + \beta z)) - F_{\text{scatt}}^{\sigma^-} (\omega + kv - (\omega_0 - \beta z))$$

$$\approx -2 \frac{\partial F}{\partial \omega} kv + 2 \frac{\partial F}{\partial \omega_0} \beta z$$

$$= F_{\text{molasses}} + F_{\text{Zeeman}}$$

$$= F_{\text{damping}} + F_{\text{restoring}}.$$  

The imbalanced radiation pressure caused by the interaction of the Zeeman-split sublevels and the circularly polarized light creates a overall force that is both damping and restoring.

5. Techniques Beyond Magneto-Optical Trapping

In a magneto-optical trap, atoms reach temperatures $\sim 100\mu\text{K}$ level. The atomic cloud needs to be cooled three orders of magnitude further to reach the temperatures necessary for BEC. To get there in a setup such as ours, we first briefly turn off the magnetic fields for a period of polarization gradient cooling. The next step is magnetic trapping, but first, the ensemble is optically pumped into the $(F = 2, m_F = +2)$ state, increasing the number of magnetically trapped atoms. In an atom chip apparatus, the atoms are then transferred from the magnetic trap to the atom chip trap. The final step is forced radio-frequency evaporative cooling. An RF ‘knife’ is used to remove the atoms with the highest energy, cooling the rest of the ensemble after thermal equilibration, akin to blowing on a hot cup of coffee. Once the cloud reaches $T_c$ and condenses, properties like temperature and atom number are measured via resonant absorption imaging.
CHAPTER 3

The Experimental Apparatus

1. A Brief History of BEC Apparatus and The Atom Chip

The original BEC apparatus were massively complicated and space-inefficient setups geared towards the exploration of cold atoms physics. Wolfgang Ketterle’s BEC system at MIT, shown in Figure 3.1, just barely fit on an 8’x 4’ optical table [21]. The traditional optomechanical and ultrahigh vacuum (UHV) architecture used for early Bose-Einstein condensation was built with function taking precedence over form; trapping atoms in large glass vacuum cells. Months before the first observation of BEC in June of 1995, a group at the California Institute of Technology prophesied the use of magnetic fields for creating microscopic atomic traps; anticipating the formation of “Bose clusters” [22]. In the late 1990s, a group in Austria began guiding cold neutral atoms using current carrying wires [23]. This idea was then extended to trapping and guiding atoms using nanofabricated wires on a substrate, dubbed the atom chip [24]. These efforts culminated in the first demonstration of BEC on an atom chip in 2001 [25].

![Ketterle apparatus at MIT.](image1)

![ColdQuanta RuBECi with physics platform.](image2)

**Figure 3.1.** From [21]. Early BEC apparatus vs. modern miniaturized variant.
2. ColdQuanta and the RuBECi

Founded in 2007 by Professor Dana Anderson, ColdQuanta is a quantum atomics company based in Boulder, Colorado. They specialize in the design and manufacture of component and system-level products for ultracold atom physics experimentation, including fully integrated standalone ultracold atom systems, glass cells, custom atom chips, and corresponding electronics. Pictured in Figure 3.3, the RuBECi® is a compact (12.5 × 12.5 × 24) cm self-contained two-chamber UHV system designed to simplify BEC production [27]. The top wall of the upper cell is formed by an atom chip, which can be customized to suit particular experimental goals.

With the demonstration of BEC at the microscopic scale, the opportunity arose to miniaturize BEC production apparatus. One of the primary goals of this endeavor was to account for the influence of gravity on atom-trapping potentials. This was first accomplished by an experiment in free-fall using a drop tower, then by zero-g airplanes, sub-orbital rockets, and recently, in NASA’s Cold Atom Laboratory (CAL) aboard the International Space Station (ISS) [26]. Launched in 2018, CAL is a multi-user atom chip apparatus orbiting the earth in continuous free-fall, developed to study the effect of microgravity on BEC dynamics. Areas of experimentation include matter-wave interferometry and hollow ‘bubble’ condensates produced using radio-frequency dressing [7].
This is a truly remarkable physical feat in its own right, as there can exist a *nine* order of magnitude temperature differential between the room-temperature chip substrate and a condensate over a distance of just a few \( \mu m \) [28]. Our RuBECi is equipped with a double-Z trace window atom chip, pictured in Figure 3.2.

Figure 3.3. Adopted from [29]. The RuBECi tabletop BEC apparatus.

Thermal atomic vapor is supplied by an alkalai metal dispenser in the lower 2D MOT vacuum chamber, which releases (in our configuration) natural abundance rubidium when driven with DC current. This means that the vapor created is comprised of approximately 72% \(^{85}\text{Rb}\) and 28% \(^{87}\text{Rb}\) [30]. The chambers are separated by a silicon pinhole 0.75 mm in diameter [31], allowing for large rubidium vapor pressures (\(10^{-7}\) Torr) in the lower (2D) chamber while maintaining UHV (\(10^{-9}\) Torr) in the upper (3D) chamber for BEC [30].
3. The Lundblad Ultracold Atom Lab

The ultracold atom lab at Bates College has two BEC-capable apparatus. The first, dubbed ‘BEC1’ was constructed in 2010, and is still in use today, albeit with diminishing frequency. The other apparatus—the one used in this project—is based on a RuBECi; given the name ‘NASABEC’ after being fitted with parts used in the development of CAL at NASA’s Jet Propulsion Laboratory (JPL) [32]. The light for laser cooling is provided by a Vescent Photonics D2 780nm laser system. The laser frequency is dynamically locked to the crossover resonance $\sim 133$MHz to the red of the $(F = 2) \rightarrow (F' = 3)$ cooling transition, with feedback from Doppler-free saturated absorption spectroscopy performed on a vapor cell of rubidium. Frequency lock is maintained with a high-speed servo that rapidly modulates the current of the laser. Repumping light, also provided by a Vescent Photonics laser diode, is locked to the $(F = 1) \rightarrow (F' = 2)$ transition $\sim 6.8$GHz away from the trapping light. The power of both repump and trapping light is then boosted by tapered amplifiers (TA)s. A TA is a device that achieves laser gain by providing pump current to a waveguide through which the laser propagates [6]. At the typical operating current of 1750 mA, the trapping TA amplifies the laser seed power of 40 mW to around 600 mW. The final laser detuning of -23 MHz is achieved by two successive passes through an acusto-optical modulator (AOM). Finally, the light is ready for magneto-optical trapping.

4. The “NASABEC” Aparatus

The experiment is located on a dedicated, pneumatically stabilized optical table, occupying roughly 1.5 m² of area. The RuBECi acts as the fundamental building block of the total experimental apparatus. Additional supportive equipment is required for laser cooling, magneto optical trapping, RF forced evaporative cooling, and magnetic trapping. The major components of the apparatus are:

- Vescent Phontonics D2 frequency-locked laser system
- ColdQuanta RuBECi with 2D+ and 3D MOT chambers
- ColdQuanta “JPL double-Z window” atom chip
- ColdQuanta Quadrupole Coil Assembly
- ColdQuanta Two-Channel Atom Chip Driver (×2)
- Agilent Technologies MicroVac ion vacuum pump
Frequency-locked light is supplied to the table via two single-mode optical fibers, one for the master laser (trapping) and one for the repump laser. Incoming light is distributed into three main optical pathways: 1) 2D+ MOT, 2) 3D MOT, and 3) push beam, as shown in Figure 3.4. The push beam, derived from trapping light, is directed in the $+\hat{z}$ direction with respect to the center vertical axis of the RuBECi. It strikes the reflective silicon pinhole, providing an additional axis of cooling for the 2D MOT, thereby constituting the “+” in 2D+ MOT. The share of the total laser power each pathway receives is controlled by a $\lambda/2$ waveplate-PBS combo for the push beam, and another $\lambda/2$ waveplate-PBS combo for the balance between the 2D and 3D pathways.

5. History of the Bates-Owned RuBECi

Originally delivered to the college in 2014, the Bates RuBECi has had a rather tumultuous history [32]. In 2016, when Daniel Paseltiner (‘16) was conducting his honors thesis project, the ion pump included with the RuBECi failed, halting progress until a replacement was shipped out. Luckily, the ultra-high vacuum can likely persist without an ion pump for $\sim$1 month before reaching a pressure that requires roughing. Unfortunately, shortly after the new pump was installed, no fluorescence could be observed in the lower chamber, the result of a complete vacuum failure. A fish-scale fracture was discovered in the glass-silicon interface between the upper vacuum chamber and the atom chip [6]. After determining that the chip was the culprit, the RuBECi was returned to ColdQuanta for repair. Two years later, the newly refurbished RuBECi arrived and was re-installed on the optical table. In the fall of 2019, following three years of dormancy, the work on this project began [32].
The height of the push beam is lowered in a periscope to 1.30 in above the table so that it can get underneath the lower vacuum chamber. It is also expanded in a telescope to maximize the portion of the experiment's bore that it covers. Once the push beam reaches the vacuum chamber a ccd camera is coupled onto its path using a PBS to image the 2D MOT from below.

The only parts of the experiment's optomechanical system left to be dis-

Figure 3.4. Adopted from [6]. Schematic diagram of the optical pathways in NASABEC.
Figure 3.5. The 2D MOT (yellow) and 3D MOT (red) laser cooling optical pathways, and the push beam (blue). Note that the X-Y plane is parallel to the optical table, while the Z axis is normal to the table.
CHAPTER 4

The 2D+ Magneto-Optical Trap

The purpose of a 2D MOT is to create a cold atom flux, which acts as a precursor for a 3D MOT. Physically, instead of creating a quasi-spherical trapped cloud, the 2D MOT creates an elongated quasi-'cigar shaped' flux of atoms. The so called “push beam,” which is aligned to be collinear with this cylindrical trap, provides cooling in the third dimension and effectively forces atoms to travel through the silicon pinhole that connects the 2D and 3D chambers.

1. Planning Phase

The work for this thesis began the week of the 16th; September 2019. The first task was to discuss the current state of the apparatus. The main glaring deficiency was the lack of an optical connection between the lab’s frequency-locked laser light source and the table where the experiment was built. NASABEC is separated from the table that houses the laser source architecture by ~1 meter of open walkway, meaning that the only practical solution was to run a section of optical fiber between the two tables. Not only was there no connection, there also was no established means of diverting the trapping or repump light from BEC1. The second major deficiency was the unknown condition of both the vacuum and alignment/polarization of virtually every optic in the apparatus. In this chapter, we explore the entire process of achieving a 2D+ MOT, evolving from a bare optomechanical structure to a clear, visible MOT.

2. Supplying Light to the Experiment

Before any work searching for a MOT could begin, the experiment needed to be supplied with light of the correct wavelength, frequency detuning, and power. The two major sources of light in our lab, detailed in Chapter 3, are the trapping and repump lasers. Once their light has been amplified, polarized, and shifted to the correct frequency, it is ready to be transmitted to the experiment via optical fiber coupling. The first task of this project was to devise a semi-permanent manner of diverting light from BEC1 to NASABEC, then couple that light into optical fibers at sufficient efficiencies, and finally run that fiber to the experiment.
2. SUPPLYING LIGHT TO THE EXPERIMENT

The semi-permanent diversion was accomplished with flipper mirrors, a type of optical stage that can be precisely and reliably changed between two 90° separated orientations. This approach was chosen to avoid the frequent and tedious realignment involved with switching between operation of BEC1 and NASABEC. We implemented a motorized flipper mirror for the trapping pathway, and a manual variant for the repump pathway. The existing and new configurations are shown in Fig. 4.1. The ThorLabs motorized flipper is capable of 50 µrad flip-to-flip repeatably, which is the maximum angular misalignment that could occur between flips [33]. This specification is important considering the high precision alignment necessary for efficient optical fiber coupling.

To couple into an optical fiber, two degrees of freedom (typically two mirrors on precision tilt mounts) in the optical pathway are required. With only one mirror, each adjustment would cause the angle of the input beam to deviate with respect to the fiber axis. Depending on how well a source is coupled into a fiber, it will suffer different amounts of attenuation due to absorption losses. Coupling efficiency is defined as the input power divided by the output power. High efficiency, characterized by the input laser beam being as collinear with the axis of the fiber as possible, can reach 90+%. For our purposes, 50-70% is sufficient. It was decided that the ideal location for both the repump and trapping flipper mirrors was directly before the respective fiber coupling apparatus for each pathway. This meant that the mirrors wouldn’t interfere with any other existing optics. After each flipper was installed, roughly aligned, and locked in place, the fiber coupling process began. Using a nW capable power meter, initial coupling was made. By adjusting the tilt mounts corresponding to each degree of freedom simultaneously, the beam was iteratively “walked” until the highest output signal was obtained. The working efficiency reached for both trapping and repump fibers was roughly 60%.

Now that a physical connection was established between the optical tables of the source lasers and NASABEC, work could begin realigning the optics in the experiment. Mapping out each optical path, depicted in Figure 3.5, helped solidify my understanding of the optical architecture before deciding where work needed to be done. In the 2D MOT laser cooling pathway, the first set of optics is a half waveplate and PBS. This junction serves to split off a small portion of the trapping power for the push beam. At the cube, the trapping and repump beams are combined. The next λ/2-PBS combo is the main split between the 2D and 3D MOT pathways. On the 2D side, the following λ/2-PBS combo splits the light and determines the power balance of the
X and Y beams of the 2D MOT. Next, the X and Y beams are broadened, made elliptical, and sent through the first of two sets of $\lambda/4$ waveplates. These change the polarization of the X and Y beams from linear to circular polarization. The angular orientation of these plates with respect to the normal of the axis of the beams is critical to creating the helicity necessary to drive the $\sigma^+$ and $\sigma^-$ transitions in the MOT.

![Figure 4.1. The existing trapping optical path for BEC1 (red), and the newly established path for NASABEC (green). The motorized flipper mirror is located at the intersection of the red and green pathways.](image)

The goal of the 2D MOT is to trap and cool as many atoms as possible along the axis of the pinhole. Capturing more atoms from the surrounding background vapor pressure generates a greater flux into the upper chamber, meaning more atoms for 3D MOTing. Generally speaking, the larger the trap, the more atoms it is capable of trapping. The size of a trap is determined by a number of factors, the most important being the cross-sectional area of the laser beams used for the cooling/repumping process. The roughly $\sim1\text{mm}$ diameter Gaussian beam that’s
emitted from the lens of the fiber source is not sufficient in this regard. To maximise the cross-
sectional area of both the 2D and 3D MOT beams, telescopes expand the beams from circular
\(\sim 1\text{mm} \) diameter beams to a elliptical beams with a horizontal beam waists of \((10.8 \pm 0.4) \text{ mm}\) and vertical waists of \((20.2 \pm 0.6) \text{ mm}\) \cite{6}.

After coupling, we dialed up the laser power to roughly 50 mW, (measured on the NASABEC trapping source fiber) and discovered that the initial alignment for the 2D MOT was serviceable. Light was reaching the X-Y split junction without significant interruption. However, the beams were far from elliptical after passing through the telescopes. By adjusting the X-Y tilt of the mirror before each telescope, the beams were brought back to sufficient ellipticity. While the alignment of the beams with respect to the vacuum cell was not crucial at this point, it was roughly corrected to make sure both trapping and repumping light was incident on the cell. Now that the properly shaped and roughly aligned light was reaching the 2D MOT chamber, it was time to determine the condition of both the vacuum and the dispenser.

3. Fluorescence

Arguably the most critical component of the entire experimental apparatus is the source of \(^{87}\text{Rb}\). When driven with current, the alkali-metal dispenser contained in in the lower RuBECi UHV chamber produces a vapor of rubidium atoms. In our lab, this current is supplied by a custom fabricated constant current source, pictured in Figure 4.2. It has a tunable range from \(\sim 0-5 \text{ A} \). The first major goal in this thesis was to observe fluorescence. Since the sudden depressurization event in 2016 to the beginning of the work of this thesis, the dispenser had not been operated. This was a major concern, with the possibilities of degradation during the dormancy period or damage upon initial re-testing equally worrisome. It was decided that the safest approach was to independently test the current supply before operating the dispenser. The unit was carefully disconnected from the RuBECi and removed from its rack mount. Using a test load resister, the current and voltage of were measured to be 3.6 A at 1.9 V.

The current adjustment was handled by a small trim potentiometer inside the unit. This meant that there was no ability to control the current when the supply was rack-mounted. To choose a starting current, we consulted the RuBECi Product Manual. In it, ColdQuanta recommends an initial value of 3.5 A for observing fluorescence. However, based on our mounting concerns about the condition of the dispenser, and the following warning in the manual \cite{30}:
3. FLUORESCENCE

**WARNING!**

Do **NOT** apply more than 4.5 A of current to the dispenser. Applying more than 5 A, *even for just a few seconds*, will release a significant quantity of Rb from the dispenser, enough to completely coat the walls of the 2D MOT chamber. This not only depletes the available Rb in the dispenser, but it also leaves the MOT chamber opaque to laser beams. Significant quantities of Rb can accumulate in the ion pump, possibly causing irreparable damage. We strongly recommend using a fuse or a circuit breaker to protect the Rb dispenser from too much current.

![The custom-built constant current source.](image)

**Figure 4.2.** The custom-built constant current source.

we decided to start with a very conservative value of 2.5 A. After determining that the supply was outputting the desired current using an ammeter, it was reinstalled and reconnected to the RuBECi.

To observe fluorescence, a method of imaging the 2D MOT chamber is required. In our setup, we use a ThorLabs CMOS camera positioned to image the MOT along its axis from below. At the bottom of the lower chamber, there is a circular viewing window. This acts as a visual guide for aligning the camera. Using the camera connected to a computer with companion software from ThorLabs, we were able to observe a blurry image. Initial alignment and focusing of the camera was difficult considering that there were few visual landmarks to
use for referencing. However, we were able to center the bottom chamber window in the frame, which was sufficient for observing fluorescence. With the camera active, trapping and repump beams aligned on the cells, and their frequencies locked, the current supply was powered on at 2.5 A. Ready to shut off the power at the first sign of an issue, we patiently waited for any change of brightness on the monitor. Soon enough, as the vapor pressure of rubidium increased, the brightness of the area inside the chamber window began to gradually increase. To prove that this behavior was indeed fluorescence, the trapping laser system was unlocked, and the laser current was coarsely modulated.

![Image](image.png)

**Figure 4.3.** $^{87}$Rb vapor intensely fluorescing in the lower vacuum chamber. The small, cylindrical grey object at the bottom is the alkali metal dispenser.

This caused the brightness to correspondingly increase and decrease, meaning that this was in fact true fluorescence of rubidium. This event proved not only that there was an active vacuum in the RuBECi UHV chamber, but that both the current supply and the dispenser were functioning nominally.

### 4. X and Y Beam Alignment and Retroreflection

Now that the dispenser was shown to reliably produce a vapor pressure of rubidium, we were ready to begin preparing the optical conditions necessary for magneto-optical trapping. In the case of both the 2D and 3D MOT, the alignment of the laser cooling beams with respect to the cell and each other is critical. In order to create an effective trap, the beams must all intersect such that the region of overlap is maximised. The beam intersection area must also spatially
coincide to the magnetic field minimum. Finally, the beams must be precisely retroreflected such that the incident beams are collinear with the reflected beams.

With these restrictions in mind, work began honing the alignment of the X and Y cooling beams. Beyond power meters and 7/64” hex keys, the laser physicist’s most invaluable laboratory tool is perhaps the standard paper business card. Beam position, shape, and path can be visualized with different variants of these cards. Brighter beams make visual determination of position more accurate, so every mW of source laser power was diverted to the 2D pathway from the 3D and push pathways using the 2D-3D power split waveplate. Before aligning the beams, we needed to make sure their shape was correct. As mentioned previously, the laser beams incident on the lower vacuum chamber are enlarged by telescopes adjacent to the MOT cell. Maximising beam size is critical for adequate trap volume and ease of alignment. By tuning the vertical and horizontal alignment of the input mirrors to the telescopes, the ellipticity of each beam was further optimised.

The next step in alignment was one of the most critical: for the MOT to exist, the cooling beams need to be as perpendicular to each other as possible, and must be collinear in incidence and retroreflection with respect to the axis intersecting the center of the cell. The area of intersection of the cooling beams ultimately determines both the physical orientation and shape of the MOT within the cell. Ensuring a center-justified beam intersection within the cell is critical for aligning the 2D+ MOT flux with the silicon pinhole. The significance of the flux-pinhole relationship will be discussed further in Chapter 5.

Starting with the Y axis, the incidence mirror was adjusted such that the center mass of the elliptical beam was visually centered on the cell. Aligning the retro mirror was not as straightforward. In order to visualize the pathway of the retroreflected beam without blocking its source, the so-called “pinhole method” is utilized. This ingenious method is elegant in its simplicity. A ∼1mm hole is made in a piece of paper, and the paper is placed in the path of the expanded MOT beam before it reaches the incidence mirror. This allows a portion of the expanded beam to continue, be retroreflected, and return to the paper. To achieve collinearity, the retro mirror must be adjusted such that the small dot created by the returning light disappears through the pinhole. Once this was accomplished with the Y axis, the same procedure was performed on the X axis. Another helpful technique involves rapidly waving a card along the axis of a beam. With sufficiently dim ambient light, the action of moving the
card back and forth allows one to visualize the path of the beam, which is helpful in determining alignment characteristics like perpendicularity.

5. Polarization Analysis

The functional mechanism of magneto-optical trap is based on the polarization of light. As discussed in Chapter 2, driving the correct atomic transitions necessary for creating a position-dependent optical force, requires circularly polarized trapping light. The large X and Y $\lambda/4$ waveplates, approximately 1” in diameter, are the largest in the experiment. Waveplates of this size are not inexpensive, but are necessary to accommodate the incident beam dimensions. The last polarization optic of our concern is the initial $\lambda/2$ waveplate, which controls the power balance of the X and Y beams. By adjusting the orientation of this waveplate, the X and Y beam powers were balanced using a power meter. Now convinced that every independent variable was optimised, polarization was the final parameter to adjust in the search for a 2D MOT. Two major considerations needed to be made with regards to the 2D MOT waveplates:

First, each beam requires two $\lambda/4$ waveplates, one for incidence and one for retroreflection. The waveplates attached to the retro mirrors—used to correct the helicity of the cooling beams—do not need adjustment.

Second, because of the geometry of the quadrupole magnetic field, each of the orthogonal cooling beams must have opposite helicities. Adding to the complexity, there are two possible helicity permutations

$$[(X \rightarrow \text{right-handed}), \ (Y \rightarrow \text{left-handed})]$$

or

$$[(Y \rightarrow \text{left-handed}), \ (X \rightarrow \text{right-handed})],$$

but only the permutation arranged properly with the magnetic field can drive the correct atomic transitions needed for the existence of a MOT. In principle, the polarity of the magnetic field could be ‘flipped’ to accommodate either orientation, but in the case of the RuBECi, the field for the 2D MOT is provided by a set of hard-mounted permanent magnets, meaning that the field’s polarity is non-adjustable (within practical reason). Therefore, finding the correct polarization...
permutation was essentially a matter trying each one separately. To determine if a beam had right or left-handed circular polarization, a polarization analyzer was used. The waveplate in the analyzer is calibrated such that incident circular polarization exits the PBS as either vertically or horizontally polarized light. For simplicity, when all of the incident light passes *through* the PBS in the analyzer, we define the incident circular polarization state to be ‘T’ for ‘transmitted.’ When all of the incident light is instead *reflected* 90 degrees, we define that to be ‘R’ for ‘reflected.’ Considering these naming conventions, the goal of this alignment exercise was to adjust one beam’s waveplate such that the light incident on the cell is T, and the other is R.

Considering that the physical orientation of the polarization analyzer with respect to the beam being analyzed was highly sensitive, the device needed to be hard-mounted to the optical table. This presented the first major hurdle in this experiment: mounting the analyzer deep within an already crowded optical setup. For the Y optical path, there was just enough room between the MOT chamber and the retro mirror to fit the analyzer. Using a necessarily convoluted arrangement of 1/4" rods and clamps, it was moved carefully into place. Then, while adjusting the Y $\lambda/4$ waveplate, the resulting T and R beams were observed. When all T light was extinguished, we were confident that the Y beam was now R polarized. For the X beam, there was absolutely no clearance for the analyzer, meaning the retro mirror had to be temporarily removed. Sacrificing the retro alignment was a necessary consequence. After marking the existing position of the retro mirror on the optical table, the mirror was carefully removed, and the analyzer was installed in its place. For T polarization, the X waveplate was adjusted such that all R was extinguished. The retro mirror was then replaced and realigned using the pinhole method as before. Finally, with Y set to R and X set to T, the first polarization combination was ready to be tested.

6. Search for 2D MOT

Visual observation is the most practical method of confirming the existence of a 2D MOT. Using a high sensitivity camera, its signature faint fluorescence within the vacuum chamber can be detected. In the close quarters of NASABEC, we employ a small-footprint CMOS camera by ThorLabs. Light from the fluorescing $^{87}$Rb atoms travels through a circular glass port on the bottom of the 2D MOT chamber. After being reflected 90° by a 45° mirror below the
chamber, the light is finally directed towards the camera’s aperture by a PBS. With this setup, the MOT can be imaged along its axis, the same axis as the pinhole connecting the two vacuum chambers. Imaging along the axis is ideal because the MOT appears as a clear dot, an obvious visual landmark. Not knowing exactly what to look for, we consulted with Dr. David Aveline of NASA’s Jet Propulsion Laboratory (JPL). He kindly provided example images of a properly functioning 2D MOT, shown in Figure 4.4.

![Figure 4.4. Example of properly aligned and imaged 2D MOT.](image)

Since the observation of fluorescence, the camera had not been adjusted. In the camera’s field of view, a small, relatively opaque circular object was visible. We naïvely assumed that this object, pictured in Figure 4.5, was the pinhole. After failing to observe any MOT-like behavior, we decided to readjust the camera. By moving the camera back and forth with respect to the PBS, the plane of focus was shifted. After substantial fiddling with the camera’s orientation, a very convincing circular landmark, shown in figure Figure 4.6(a), was located.

With the MOT waveplates set in the \([X \rightarrow T, \ Y \rightarrow R]\) permutation, the search method consisted of slightly detuning the orientation of the waveplates, retro mirrors, and telescopes of each cooling pathway, and looking for a corresponding change in behavior on the screen.
Satisfied that no significant behavior could be observed, we decided to switch to the other permutation. This decision was not made lightly, as the switch involved once again removing the X retro mirror. After re-adjusting the MOT waveplates such that \([X \rightarrow R, \ Y \rightarrow T]\) and replacing/re-aligning the X retro mirror, the search continued. After tweaking several of the previously stated parameters once again, a small phenomena was observed when detuning the Y waveplate. By adjusting the contrast of the camera, a distinct bright spot was observed. The spot disappeared when the Y waveplate was detuned, then reappeared again when it was retuned. This dramatic dependence on polarization, as shown in Figure 4.6, is evidence that the bright spot was in fact a 2D MOT.
CHAPTER 5

The 3D Magneto-Optical Trap

Now that a strong and stable 2D MOT was established, it was time to turn our attention to the 3D MOT. Many challenges were experienced along the way. Adding another cooling pathway dramatically increases the complexity of both the experimental conditions needed for successful trapping, and the phenomena that occur within the trap. In addition to the further optomechanical adjustments, the magnetic field is no longer supplied by permanent magnets, but by coils, meaning another degree of freedom was introduced into the situation. The 3D MOT is critical to BEC experimentation because it allows physicists to cool atoms to \( \mu \text{K} \) temperatures whilst confining them in a highly deterministic manner. Having a reliable, high performance 3D MOT in the RuBECi is critical for the remaining steps in achieving BEC, including magnetic trapping, atom chip trapping, and forced RF evaporative cooling. In this section, I present the iterative experimental steps toward 3D MOTing in the RuBECi, including optical alignment, polarization analysis, and magnetic field manipulation. I also discuss how 3D MOT behavior can be quantified, and report on several experimental results. Below are the four major adjustments to the apparatus required before the search for a 3D MOT could begin.

- Alignment and beam profile conditioning of the 4 main laser cooling optical pathways
- Adjustment of the 4 main \( \frac{\lambda}{4} \) waveplates
- Connection and testing of the quadrupole coil assembly
- Installation of CCTV camera

1. Preliminary Alignment of Laser Cooling Pathways

The project’s focus was now set on preparing the conditions necessary for 3D magneto-optical trapping. After an initial assessment, it was determined that the 3D MOT laser cooling optical pathways in the apparatus had completely lost their alignment during its period of dormancy. Thus, the first step was to coarsely realign each mirror in each pathway. To help with visually determining the beam location at any specific point, the laser power balance was now shifted completely towards the 3D pathway. The repump light was physically shuttered to
prevent it from interfering with the alignment of the trapping light. Starting at the 2D-3D split, each mirror mount was iteratively adjusted using their horizontal and vertical screws. Proper alignment entailed centering each beam on the next optic in the pathway. Employing the ‘card fanning’ method described in Chapter 4, each beam was directed, mirror by mirror, towards its final destination: the 3D MOT vacuum cell. The path taken by each beam was determined using the schematic diagram in Figure 3.5. The telescopes for the 3D MOT, unlike those used for the 2D MOT, consisted of only circular convex expansion lenses, thus forming an enlarged circular beam profile $\sim 1.5$ cm in diameter. Each independent cooling beam required its own periscope to raise it to the required height corresponding to the vacuum cell. Alignment of the periscopes was completed in a similar fashion to the previous optics. Atop the periscopes, the main 3D MOT mirrors are mounted. There are 6 mirrors that need adjustment, 4 that direct the independent X and Y cooling beams, and 2 retroreflection mirrors in the Y pathways. Each beam was aligned—using the 45° mirror mounts—such that its circular dot, visualized on a card, struck the 3D vacuum cell.

As with the 2D MOT, the goal of the 3D MOT laser cooling beam alignment is twofold: 1) to have each beam (including retroreflected beams) intersect each other in the center of the cell, and 2) maximise the region of beam intersection. For the independent beams along the X axis, this was accomplished to a preliminary degree by using the card waving technique. Determining intersection of the X beams was deceptively simple. By placing a card in the beam path, dots from the $+\hat{x}$ and $-\hat{x}$ beams would appear on opposite sides of the card. Sufficient alignment was reached by adjusting each mirror such that the two dots overlap. In the Y axis, the beams were first trained on their opposing retroreflection mirrors. Each retro mirror was then adjusted using the previously described pinhole technique, ensuring collinearity of the incident and reflected beams.

### 2. Polarization Analysis

Now that the laser cooling beams had a preliminary alignment, their polarization needed to be analyzed to ensure the proper configuration for magneto-optical trapping. As with the 2D MOT, the state of the 3D MOT $\lambda/4$ waveplates was unknown. To prevent wasted time searching for a MOT under the false impression of correct polarization, we decided to completely re-adjust them all. The 4 waveplates needing adjustment were the $+\hat{x}$ and $-\hat{x}$ waveplates, and the incident
waveplates of the Y axis pairs. As before, the circular polarization of the retroreflected beams is not affected by rotation of the retro $\lambda/4$ waveplates.

The logistics of polarization analysis for the 3D MOT were far simpler than that of the 2D MOT. The 3D MOT mirrors and waveplates are secured using ‘cage-mount’ architecture. The cage-mount architecture uses a system of rods, plates and mounts to simplify the alignment and assembly of optical components \[34\]. Conveniently, the polarization analyzer was constructed with this in mind. The cage-mount plate on the analyzer allows it to be attached quickly and solidly to the MOT mirror-waveplate mounts. This avoids the need to construct a convoluted custom 1/4” post mount to reach the tall MOT mirrors. In the true spirit of experimentation, I didn’t realize this until already having built said convoluted mount.

By mating the holes in the plate of the analyzer with the corresponding rods of the MOT mirror-waveplate mount, all three components were aligned and secured together. To begin polarization analysis, the repump laser was shuttered, and all trapping laser power was directed to the 3D MOT pathway. Due to the quadrupole magnetic field geometry, the polarization of each cooling axis needed to alternate in order to drive the correct atomic transitions for
magneto-optical trapping. In practical terms, this means that opposing waveplates along the same axis (+\( \hat{x} \) and -\( \hat{x} \) for ex.) require the same helicity, but the X and Y axes require opposite helicities. With this in mind, we decided to assign ‘T’ polarization to the Y beams, and ‘R’ polarization to the X beams. Using the polarization analyzer, each \( \lambda/4 \) waveplate was carefully adjusted such that the light from the desired polarization state was maximised, and light from the opposite state was completely extinguished.

3. Quadrupole Coil Assembly

In the RuBECi, the 3D MOT is created using a quadrupole magnetic field. This type of field can be produced by a pair of coils in anti-Helmholtz configuration, which simply means that the current in each coil is being driven in opposite directions. This type of configuration produces a magnetic field gradient which varies in magnitude and direction with position. The Helmholtz configuration, with current running in the same direction in each coil, produces a magnetic bias field. Based on the geometry of a quadrupole magnetic field, the atoms in a MOT are forced towards the area where the magnitude of the magnetic field is a minimum. With equal and opposite currents, this field zero is equidistant between the coils. Combining a gradient field with a bias field allows for precise spacial positioning of the magnetic field zero, which is critical for both the alignment of the MOT and the cancellation of external bias fields.

The ColdQuanta Quadrupole Coil Assembly installed on the Bates RuBECi is a convenient and feature-rich solution, which combines multiple coil sets with adjustability and ease of operation. Our specific unit saw use at NASA’s Jet Propulsion Laboratory (JPL) before migrating to the aptly named NASABEC [32]. The assembly contains eight rectangular coils mounted to an anodized aluminium frame. The frame rides on 4 coil rails that are attached to the main mounting plate of the RuBECi. Four independent coil pairs provide magnetic field gradient and bias fields for the X, Y, and Z axes. The following table of values from [29] shows the gradient and bias fields that can be produced with the coils.

The assembly is connected to a constant current source via a micro-D connector. The X coils and transfer coils are rated for 10 A, while the Y and Z coils are rated for 3 A. In normal steady state MOT operation, the current used in the X coils is between (0.5-1.5) A. During transport, up to 10 A is typically driven through the X coils, and as much as 12 A through the transfer coils for brief periods [29]. During the course of this thesis project, the coil temperature
3. Driving the Coils

To create gradients and bias fields, current must flow through both coils oriented along a given direction. For bias fields, current must flow in the same direction through the coil pair oriented along a given direction. By flipping the sign of the current passing through one of these coils, a magnetic gradient is created instead. The table below quantifies these bias fields and gradients:

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Bias (±X1 ± X2)</td>
<td>±19.9 G/A (\hat{x})</td>
</tr>
<tr>
<td>X Grad (±X1 ± X2)</td>
<td>9.0 G/(cm-A)</td>
</tr>
<tr>
<td>Y Bias (±Y1 ± Y2)</td>
<td>±22.6 G/A (\hat{y})</td>
</tr>
<tr>
<td>Y Grad (±Y1 ± Y2)</td>
<td>15.5 G/(cm-A)</td>
</tr>
<tr>
<td>Z Bias (±Z1 ± Z2)</td>
<td>±7.6 G/A (\hat{z})</td>
</tr>
<tr>
<td>Transfer Gradient (±T1 ± T2)</td>
<td>13.3 G/(cm-A)</td>
</tr>
</tbody>
</table>

For gradients and bias fields, the coils can be connected in series and driven with a single power supply. To create a gradient whose center does not coincide with the center of the cell, the pair of coils should be driven with unequal currents. In this scenario, each coil in a pair must be powered by its own driver.

4. Electrical Connections

Electrical connections are made to the coils through a micro-D connector that is located on the lower front of the assembly. The assembly comes with a cable for connecting the coils to appropriate current drivers. The cable has a micro-D connector plug on one end and labeled banana plugs the other. For each coil, a positive current (i.e. one flowing from the red banana plug to the black banana plug) will produce a magnetic field pointing in the positive direction. The small pins on the micro-D connector are rated for 3 A, while the large pins are rated for 10 A. Normal operation for a MOT is between 0.5 and 1 A, and approximately 2 A for trapping on the chip. For atom transport, up to 10 A is used with the x coils. For the transfer coils, peak currents up to 12 A (durations less than 100 ms) are typically used. The coils will get warm during normal operation, but must not be allowed to exceed 80°C.

was regularly monitored using an IR thermometer. When driven at ±1.5 A, the average steady state X coil temperature was approximately 50°C.

After the 3D MOT optical pathways had been roughly aligned, it was time to prepare the coil assembly for operation. For the initial MOT search, only a gradient field is needed, so the X coils were the first to be connected. Considering the incredibly sensitive nature of a MOT, two major requirements had to be met: 1) the current delivered to the coils needs to be ultra-stable, and 2) the current needs to be precisely and continuously controlled. To reliably achieve these conditions, the Kepco BOP 20-10M high-speed bipolar operational amplifier, with RMS ripple/noise of 3 mA, and precision analog control is used [35]. The first step was to attach the included breakout cable to the micro-D connector on the coil assembly using the two attachment screws. Even though the RuBECi is very securely attached to the optical table, this was done with a measure of caution. This cable converted each pin on the male micro-D connection to a corresponding standard female banana plug. Using 14 AWG ‘hook up’ copper wire rated for 15 A, each X coil was connected to its designated BOP.

Using a Gaussmeter, the magnetic field magnitude and polarity produced by each coil was measured. The meter’s probe was placed near the center of each coil and measured an opposite polarity, confirming the presence of a quadrupole magnetic field.

4. Imaging the Vacuum Cell

The search for an initial 3D MOT, as with the 2D MOT, is only feasible with the help of imaging. In this case, we used a CCTV camera, specifically the NAVCO 4850. This analog video camera functions by bombarding a phosphorus surface with an electron beam [36]. The output signal is then fed to a CRT monitor via a BNC cable. This makes for a very simple and
cheap method of imagine a MOT; a marked advantage in practicality over comparable digital solutions. The zoom lens of the NAVCO 4850 is has a focal range of (2.7-13.5) mm.

![Image of the vacuum cell with cooling beams and imaging camera.](image_url)

**Figure 5.2.** Narrow clearance between (simulated) Y axis cooling beams and the 3D MOT imaging camera.

A custom 1/4" post stand was constructed for robust positioning of the camera, which was securely attached by a conveniently placed threaded insert. Considering its relatively large size, the placement options for the camera were significantly limited by the architecture of the apparatus. The quadruple coil assembly completely surrounds the upper vacuum chamber of the RuBECi, with 4 narrow apertures for laser cooling and imaging. The only area with enough clearance for the camera and associated mounting hardware was the narrow gap between the
incident and retro mirrors on either side of the Y axis. Avoiding the obstruction of cooling beams, as depicted in Figure 5.2, further complicated this placement.

5. Search for 3D MOT

After checking and rechecking the alignment of the cooling beams on the upper cell, the retroreflection collinearity of each Y beam, the helicity permutation of the incident $\lambda/4$ waveplates, the presence of a magnetic field gradient, the existence of the 2D MOT, and the alignment of the push beam, we could finally begin the search for a 3D MOT. A roughly aligned 3D MOT appears to the camera as a small, faint dot in the center of the upper vacuum chamber. To positively confirm that a dot viewed on the display is a MOT, we expected to see it display a certain set of behaviors. First, when either of the 6 MOT cooling beams is blocked, the MOT will experience dramatically unbalanced radiation pressure, and thus the dot should instantly disappear. Second, when the beam is unblocked, the MOT should slowly load, and the corresponding visual dot should grow to its original size. This second condition is most significant considering the vacuum cell is not perfectly clean, meaning that stray specks of dust on the glass surface all appear as small, faint dots to the camera. Determining if a dot viewed on the CRT exhibits these behaviors is imperative to confirming that it is in fact a 3D MOT. Over a period of approximately 8 weeks, three distinct phases of experimentation lead to the observation of the first 3D MOT. Each new phase involved different search tactics, motivated by postulations and realizations that came about when progress stagnated.

5.1. Phase 1: Push Beam Alignment. Derived from trapping laser light, the push beam is oriented along the Z-axis of the RuBECi. To effectively force atoms into the upper vacuum chamber, the beam must travel through both the bottom aperture of the 2D MOT cell and the silicon pinhole. In principle, a 3D MOT can load from background $^{87}$Rb vapor in the upper vacuum cell without assistance from the push beam. Based on this sentiment, the alignment of the push beam was neglected until this point in the project. After many failed attempts at observing a MOT, it was time to pay attention to the ‘+’ in 2D+. Only 0.75 mm in diameter, the silicon pinhole makes alignment of the push beam somewhat arduous. The solution lies in the design of the RuBECi. To endure intense differential pressure, the delicate atom chip is structurally reinforced with a silicon backing plate. This particular model is a so-called window chip, meaning it has a transparent circular aperture designed for imaging via a microscope
5. SEARCH FOR 3D MOT

objective [30]. Thus, an unobstructed optical pathway exists from the bottom of the lower vacuum chamber to the top of the upper chamber. By adjusting the two alignment mirrors in the push beam’s optical pathway, correct alignment is achieved when a faint dot appears on a card held directly above the atom chip, as shown in Figure 5.3.

Figure 5.3. The red dot, pictured striking a card above the RuBECi, confirms the correct alignment of the push beam.

5.2. Phase 2: 2D MOT Flux Alignment. After several unsuccessful attempts to locate a MOT, the next strategy was to revisit the alignment of the 2D MOT and combat the parallax issues with the camera. The goal was to eliminate any doubt that the 2D MOT was in fact aligned with the silicon pinhole, which is critical considering how narrow the cigar-shaped MOT is. In retrospect, this alignment is far more tolerant than we initially believed; nevertheless, it was an important step. By moving the entire camera left/right or up/down with respect to the optical table, the parallax error was addressed. Using the visual measurement tool in the Thorlabs imaging software, the camera’s field of view was adjusted such that the silicon pinhole
was centered in the frame, as shown in Figure 5.4. By making each of the lengths roughly equal, we could be confident that the image of the pinhole in the background was aligned in the center of the circular aperture at the bottom of the cell. This ensured that we were accurately imaging the MOT along its axis, which was critical to the MOT’s alignment with the pinhole in the background.

![Figure 5.4. (Left) Severely missaligned and parallaxed camera position. The 2D MOT appears stretched. (Right) Ideal alignment. The bright spot in the center is the 2D MOT. Using the visual length tool in the ThorCam™ image capture application, the yellow lines indicate the distance [arb] from the circumference of the pinhole to the edge of the vacuum cell aperture.](image)

**5.3. Phase 3: Quadrupole Coil Assembly Readjustment.** The transition to this phase of experimentation was motivated by a puzzling observation during the MOT search. Multiple days of checking and re-checking every parameter yielded no evidence of a MOT. One day, while checking the alignment of the -\( \hat{x} \) incident cooling beam—a parameter that had been checked many times—I considered it with respect to the position of the X coils. Pictured in Figure 5.5, the dot on the card is obviously not centered with respect to the coil. I realized that a 3D MOT absolutely could not exist with this dramatic vertical misalignment.

*The magnetic field zero must coincide with the cooling beam intersection area.*
To remedy this problem, we considered three possible solutions: 1) move the field zero by driving the Z bias coils, 2) move the +x and -x mirrors downwards, or 3) slide the entire coil assembly upwards. While all three options are all technically possible, option (2) would require cutting the custom mirror posts, and option (1) would add more ambiguity to an already elaborate search process. Option (3) proved to be a simple and effective fix. To move the coils, the set screws at each rail interface on the aluminum housing needed to be loosened. Then, the entire assembly was very carefully pushed upwards roughly 5mm, as shown in Figure 5.6.

Now that the X beams were aligned with the field zero, my attention turned to the Y beams. Unlike the Y beams, the X beams remain perpendicular to the coils and collinear to
Figure 5.6. Carefully sliding the coil assembly upward by hand along the 4 alignment rails after loosening the corresponding set screws.

each other when passing through the chamber. However, the trajectories of the Y beams are not as predictable. They cross in the center of the trap, forming an ‘X’ arrangement. For a MOT to exist, there must be some overlap of all three cooling beams, meaning that the $+\hat{y}$ and $-\hat{y}$ beams must overlap both each other and the X cooling axis. To visualize the alignment of the Y beams, a piece of tape (Figure 5.7) was wrapped around the exterior of the coil assembly, bisecting the X coils.

It was clear that the Y beams were not correctly aligned with respect to the X beams. Minor adjustments were made to the lower Y-beam mirror mounts, and then we prepared for another 3D MOT attempt. This time, with a $\pm 1.3$ A X coil gradient, a minuscule dot (Figure 5.8) appeared on the CRT. When either one of the six 3D MOT beams was obstructed, the MOT was extinguished, and immediately began to slowly grow and returned to its original intensity within 3-4 seconds after being unblocked. Disturbing the magnetic field gradient by waving a bar magnet around the coil assembly caused the dot to correspondingly move around around the screen [37]. This behavior, combined with the slow loading action, was proof that the dot was in fact a 3D MOT.
6. The Flux-Nourished Regime

An ideal 3D MOT for BEC research in the RuBECi is large and loads quickly. This is achieved with a stable 2D MOT aligned such that its atom flux intercepts the 3D trapping region. This ‘flux nourishment’ is critical to high MOT performance. To have flux nourishment,
two conditions need to be met: 1) the 2D MOT flux must be aligned with the silicon pinhole, and 2) The capture region of the 3D MOT must be aligned with the axis of the flux. If either of these conditions are not met, the 3D MOT will slowly load from the background $^{87}$Rb vapor pressure, which is not ideal. With every indication that the flux was aligned with the pinhole, the first condition was satisfied. The final parameter to adjust was the position of the MOT in the cell.

The magnetic field produced by a set of coils in anti-Helmholtz configuration can be thought of as the summation of two separate constituents: a gradient field and a bias field. By offsetting the current of either coil

\[ I_{\text{coil} \ 1} = I_{+\text{grad}} + I_{\pm\text{bias}} \]
\[ I_{\text{coil} \ 2} = I_{-\text{grad}}, \]  

(5.1)

a bias field is introduced that effectively changes the position of the magnetic field zero. Since the 3D MOT exists at the magnetic field zero, the MOT’s position changes correspondingly. Practically, this is as simple as adjusting the knob on the coil’s power supply. However, considering the Kepco BOPs were located in a separate room, we exploited their analog control feature. Using BNC cables, the BOPs were each connected to their own designated SRS DS345 function generator located on the NASABEC optical table. To induce bias along the X axis, one of the X BOPs was connected to a function generator. Both coils along the Y axis, wired in series with a single BOP, produce a pure bias field.

With independent control of the X and Y position of the 3D MOT, it could be maneuvered around the cell with great precision. To scan for evidence of flux nourishment, the MOT was offset by the function generators in a sinusoidal manner. By making each axis oscillate with a different frequency (i.e. X = 1Hz and Y = 3Hz), the MOT could be moved back and forth in a raster pattern over a defined region. By increasing the magnitude of the offset, the scanning region would correspondingly increase. The push beam, if aligned correctly, should manifest as a narrow, vertical beam of photons in the center of the cell. The goal of moving the 3D MOT is to find evidence of it being disturbed by this beam. After experimenting with multiple 3D MOT positions, an X gradient offset and Y bias was found such that the 3D MOT was ‘blown away’ (Figure 5.9) at increased push beam power. Only when the 3D MOT is positioned in this
zone, affectionately dubbed the ‘blow away zone,’ can it be intercepted by the pre-cooled atoms from the 2D MOT, and thus be flux-nourished.

![Figure 5.9](image)

**Figure 5.9.** Five images showing the 3D MOT translating along the Y axis as it passes over the ‘blow away zone.’ Picture 3 depicts correct alignment for flux-nourishment.

There was no evidence of the MOT growing in size at this point. However, after increasing the dispenser current to 2.75 A (with the hope of increasing flux), and increasing the X gradient to (±1.5 A), a roughly 50% growth in size was observed. In addition, the MOT was just barely visible to the naked eye. At the very edge of the visual spectrum, the 780 nm light fluorescing from the MOT is deeply crimson in appearance. It’s one thing to see pictures of MOTs, or even to view them with a camera, but seeing one in person is truly a beautiful sight to behold. An unadulterated, macroscopic quantum object.

Disappointingly, extinguishing the 2D MOT did not affect the 3D MOT, meaning that it was still loading from background $^{87}$Rb. To attain flux nourishment, we needed to adopt a more quantitative approach. A photodiode was mounted to the optical table and trained at the 3D MOT to more closely investigate its behavior. The output was monitored by an oscilloscope. To gather light fluorescing from the MOT, a lens with a ~5 cm focal distance was attached to the photodiode. To capture the most amount of incoming photons, the photodiode was positioned such that the average voltage produced by the steady-state MOT was maximised. For the following search, the dispenser current was reduced to 2.5 A to limit saturation, and TA current upped by 100 mA to maximise laser power. All of the typical parameters (2D-3D balance, push beam power, 3D beam alignment, etc.) were iteratively tweaked. No obvious change in behavior. Frustrated, we began adjusting parameters that hadn’t been changed since the beginning of the project. Specifically, the 2D MOT retro mirror alignment.
In an attempt to rule out all other possibilities, we had inadvertently stumbled upon the bottleneck that had likely been holding the project back for weeks. When the X 2D MOT retro mirror’s vertical adjustment was tweaked, a noticeable change occurred. There was now a non-zero photodiode voltage difference between the 2D MOT being unblocked vs. blocked. Another 1/4 turn instantly caused the 3D MOT to balloon in size. It was stunning. With one minor adjustment, the 3D MOT had transformed from unresponsive and small to fully flux-nourished and 1/2 the size of the vacuum cell! Figure 5.10 depicts the magnitude of the difference.

**Figure 5.10.** Preliminary 3D MOT loaded from background (left). Flux-nourished 3D MOT (right).

Why did such a small adjustment elicit such a dramatic improvement in MOT performance? If the retroreflected X beam was misaligned such that it was directed slightly above the 2D MOT, then, in the same way the push beam ‘blew away’ the 3D MOT, it could have been blowing away the atom flux before it reached the silicon pinhole. When the retro’s alignment was tweaked, the atoms were free to be shot into the upper vacuum chamber under the influence of the push beam, directly loading the 3D MOT.

### 7. Atom Number Calibration

The performance of a magneto-optical trap is determined by how many atoms it can trap, and how fast can it can trap them. Optimization of atom number and loading rate of a MOT is instrumental in many disciplines of cold atom research. The following technique for MOT analysis is adopted from [15].
Figure 5.11. A photograph of $\sim 3 \times 10^8$ rubidium-87 atoms cooled to $\sim 100 \mu K$ in a flux-nourished 3D MOT. No digital enhancement besides in-camera JPEG compression.

The problem with determining atom number is that the a three dimensional optical molasses is very complicated. The three pairs of counterpropagating, circularly polarized beams interfere to create a spacial lattice of polarization and intensity. Taking the magnetic field into account makes the situation even more complex. To simplify the situation, the magnetic field can be neglected, and the assumption can be made that the atoms are moving within this lattice, thereby averagely experiencing all polarization states and an intensity of $6I_0$. The scattering rate of the atoms in this system is then reduced to Equation 2.11, the same as that of a two-level atom. Importantly, this allows us to calculate the number of atoms in a MOT by measuring the optical scattering rate. Using a photodiode, the output voltage generated by incoming photons can be converted to atom number. The photon detection rate of the photodiode is given by:

$$R_{PD} = R_{\text{scatt}}Nd\Omega,$$

where $R_{\text{scatt}}$ is Equation 2.11, $N$ is the number of atoms in the 3D MOT, and $d\Omega$ is the solid angle of the photodiode lens with respect to the MOT. $R_{PD}$ itself is dependent on the current $(V/R)$ output of the photodiode and it’s responsivity $\mathcal{R}$. Solving for atom number gives the final atom calibration function:
7. ATOM NUMBER CALIBRATION

\[
N(V) = \frac{8\pi \left[ 1 + 4 \left( \frac{\Delta}{\Gamma} \right)^2 + \left( \frac{\bar{\alpha}_h}{\bar{\alpha}_{sat}} \right)^2 \right]}{\Gamma \left( \frac{\bar{\alpha}_h}{\bar{\alpha}_{sat}} \right) d\Omega} \left( \frac{V}{R_h f \tilde{R}} \right). \tag{5.3}
\]

This geometric argument relies on relatively few measured parameters. The solid angle necessitates measuring the distance from the lens to the MOT, and measuring the lens diameter. Clearly, the distance from the lens to the MOT, as well as the diameter of each MOT beam must be estimated. Using this calibration function, voltage data from the photodiode can be systematically converted into atom number data, giving a quantitative perspective of 3D MOT performance.

As mentioned previously, the voltage from the photodiode is visualized on an oscilloscope. Considering that MOT loading times are on the order of multiple seconds, the scope is set to rolling trigger, with a horizontal timebase of 2-4 seconds/division. To produce a loading curve, one of the MOT cooling beams is blocked, then unblocked after a short delay. MOT loading depends on the capture rate of the 2D MOT flux, and the loss rate from one and two-body losses. By assuming low atom density, we can neglect the effect of two body losses, and write that

\[
\frac{dN}{dt} = L - \gamma N, \tag{5.4}
\]

where \(N\) is the number of atoms in the MOT, \(L\) is the loading rate and \(\gamma\) is the loss rate. Solving this differential equation for atom number yields

\[
N_{load}(t) = \frac{L}{\gamma} \left( 1 - e^{-\gamma t} \right). \tag{5.5}
\]

By excluding the loss rate, we can also determine the maximum number of atoms in the MOT at steady state

\[
N_{load}(t) = N_{max} \left( 1 - e^{-t/\tau} \right), \tag{5.6}
\]

where the time constant \(\tau\) gives the lifetime of the atoms within the trap. Loading curves in different regimes were fit to these functions, and both \(L\) and \(N_{max}\) were extracted using MATLAB. A Typical loading curve with corresponding exponential fit is shown in Figure 5.12.
An inherent limitation of this method is that it relies on multiple estimated quantities. Thus, multiple sources of uncertainty affect our results. Most significant is the uncertainty in the laser power measurements that factored into $I_0$. The problem is that the 1) the diameter of the beam incident on the MOT is larger than the diameter of the power meter aperture, and therefore some percentage of the total beam power is not measured, and 2) the MOT beams are not perfectly power balanced while running in steady state, meaning that any individual measurement would not be representative of average beam power. This was accounted for by first dividing the total power of the entire 3D MOT pathway by six, then multiplying by a power loss coefficient.

**Figure 5.12.** An example curve fit of a loading curve. Calibrated atom number vs. Time.

8. Parameter Variation

The nature of this thesis project up until flux-nourishment was purely exploratory. Although optical fiber coupling, optomechanical alignment and polarization analysis are all necessary steps toward the end goal of BEC, neither of these milestones provide substantive opportunity for experiment. As fascinating and critical as it is, even the 2D MOT can generally only be measured in a qualitative sense. The same goes for a 3D MOT loaded from background vapor. The excitement of reaching the flux-nourished regime was due not only to it’s significance in
physics and BEC production, but also to the many opportunities it opened for experimentation. The rich dynamics of the flux-nourished 3D MOT provide insight into its relationship with the 2D+ MOT. By measuring the fluorescence of the 3D MOT with a photodiode, loading rate can be measured and quantified in terms of calibrated atom number. The affect of varying important MOT parameters in the apparatus could now be experimentally investigated. In this section, I present the methodology and results of this investigation.

8.1. Influence of the 2D+ MOT and Push Beam on Loading Rate. 3D MOT loading is dominated by the 2D+ MOT. Without it, the 3D MOT can only load from background $^{87}\text{Rb}$ pressure, and will correspondingly lack density. In Figure 5.13, we compare background loading, loading only with the 2D MOT (push beam blocked), loading only with the push beam (2D MOT extinguished), and loading with both 2D MOT and push beam.

![Figure 5.13](image.png)

**Figure 5.13.** Comparison between background loading (orange), loading only with the 2D MOT (red), loading only with the push beam (blue), and loading with both 2D MOT and push beam (purple).

Clearly, the 2D MOT alone is not sufficient for quick loading. The push beam provides a critical directive boost to the 2D MOT flux, forcing atoms through the silicon pinhole to be captured by the 3D MOT, thus maximising 3D MOT size and loading rate.
8.2. Influence of 2D-3D Power Balance on Loading Rate and Calibrated Atom Number. The combined total trapping and pumping power of the experiment is typically $\sim 130$ mW. As mentioned previously, the fractional distribution of this power between the 2D and 3D MOT can be varied by rotating the 2D-3D $\lambda/2$ waveplate. When the 3D MOT is provided more power, it was observed that the density increased, and overall size correspondingly decreased. When the 2D MOT is provided more power, the 3D MOT is starved of light and shrinks until it eventually disappears. In Figure 5.14, we vary 2D-3D power distribution by rotating the 2D-3D $\lambda/2$ waveplate over a range of $30^\circ$.

Evidently, the highest performance of the 3D MOT is achieved when it is neither starved of, nor over-saturated with atoms. This correlates to a 2D-3D waveplate orientation of $\sim 72^\circ$. Note that the power measured is total power of each optical pathway, meaning that trapping and repumping power are not individually resolved.

8.3. Influence of Dispenser Current on Loading Rate and Calibrated Atom Number. Ultimately, the 2D MOT can only trap the amount of atoms emitted from the rubidium source. By increasing the current of the dispenser, more atoms are emitted, and thus the vapor pressure is increased in the lower vacuum chamber. In principle, more trapped atoms means more flux. In Figure 5.15, we investigate the influence of dispenser current on the 3D MOT. The dispenser, acting essentially as a heating element, cannot change temperature (and its corresponding flux) instantly. To compensate, each run was taken 30 minutes after the previous dispenser current readjustment, ensuring proper thermal re-equilibration.

There is a clear positive correlation between dispenser current and both atom number and loading rate, up until 2.6 A, after which, both parameters significantly drop off. Based on the RuBECi manual [30], and examples in the literature [38], an optimal current for fast MOT loading is roughly 3.5-3.8 A. Perhaps this disparity exists because the dispenser installed in our RuBECi has a higher resistance, thus releasing more rubidium atoms at a lower current than other experiments. The sharp loading rate drop off could also be due to saturation of rubidium in the lower chamber, leading to increased one and two-body losses overwhelming the tails of the cigar-shaped 2D MOT, and thereby decreasing atom flux. Either way, a 3D MOT loading rate of $15 \times 10^7$ atoms/second is sufficient for BEC production.
Figure 5.14. 30° rotation of the 2D-3D power balance $\lambda/2$ waveplate. The first graph is max atom number vs $\theta$, the second is loading rate vs $\theta$, and the third is 2D total power (blue) and 3D total power (red) vs $\theta$. 
Figure 5.15. Influence of dispenser current on atom number and loading rate.
CHAPTER 6

Path Forward

In this thesis, we have demonstrated experimental progress in an atom-chip Bose-Einstein condensation apparatus, starting with the establishment of a stable 2D MOT, and culminating in the verification, optimization, and characterization of the flux-nourished 3D MOT. The power balance analysis indicates that the 3D MOT performs best when total laser cooling power is shared equally with the 2D MOT. The investigation of dispenser current confirmed the notion that 2D MOT flux is positively correlated with the current — up until a saturation threshold. The motivation for this work still remains the same: to reach BEC in the Bates College RuBECi, eventually using the apparatus as a tesbed for comparative research with CAL and future micro-gravity experiments. The remaining steps toward this goal are clear. First, a means of simultaneously zeroing the magnetic field gradient will allow for the observation of molasses. The optical pumping of atoms in molasses will necessitate the establishment of a new fiber connection to NASABEC. After being pumped into the \((F = 2, m_F = +2)\) state, the rubidium atoms will be moved towards the chip trap with a set of transfer coils, requiring additional power supplies. Finally, when atoms are loaded into the chip trap, the focus can finally be turned to evaporative cooling and the push for the first condensate.

Extraordinary achievements in experimental physics are traditionally celebrated with a bottle of champagne. Hopefully, Bates physics students will be popping the cork for NASABEC in the near future.
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