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Sympathetic Cooling of a Bose/Fermi Mixture of Lithium to Quantum Degeneracy

by

Kevin Edwin Strecker

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

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APPROVED, THESIS COMMITTEE:

Randall G. Hulet
Randall G. Hulet, Chairman
Fayez Sarofim Professor of Physics and Astronomy

Thomas C. Killian
Assistant Professor of Physics and Astronomy

James P. Hannon
Professor of Physics and Astronomy

Houston, Texas
December, 2001
ABSTRACT

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A dual species electromagnetic trap has been developed for the purpose of studying quantum degeneracy and the BCS phase transition in $^6$Li. Since the symmetry requirements of quantum mechanics forbid collisions between identical ultra-cold fermions, the standard method of cooling atoms in a magnetic trap, evaporative cooling, will not work. To circumvent this obstacle we evaporatively cool $^7$Li, the boson, and allow sympathetic collisions between the bosons and fermions to cool the $^6$Li to quantum degeneracy. This thesis will cover the experimental details pertaining to capturing, cooling, and probing a mixture of atomic $^7$Li and $^6$Li.
Acknowledgments

This marks yet another step in my education which, as always, I could not have accomplished without copious help from my friends. Particularly, Andrew, Guthrie, Randy, Ian, Bita, and Dean. These people proved the academic and technical support that was, and is, vital to my education. There are about a thousand others whom have contributed to this work in invaluable way, but thanking everybody is the task of a Ph.D. thesis, and alas this is a masters thesis.

I also want to thank my family for the continuing support. Michelle, not only for not getting mad when I do not come home, but for all your help in proofing the thesis. My parents for the eternal support, encouragement, and always believing in me. Most importantly, I want to dedicate this thesis to the memory of my grandfather, H. A. Strecker, Ph.D.. He impressed me so much with his knowledge and wisdom that I wanted to follow in his footsteps and become a scientist.
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Chapter 1
Introduction

The motivation behind the experiments presented in this thesis is to investigate the quantum mechanical behavior of fermionic lithium-6 (\(^6\)Li). Unfortunately, under standard conditions, \(^6\)Li does not behave quantum mechanically, but behaves like a classical particle. In order to investigate the quantum behavior the atoms must be cooled down to near absolute zero (1 millionth of a degree) at densities of around \(10^{12}\) atoms/cm\(^3\). In this regime, the atoms true quantum nature becomes apparent, and can be explored.

A further aspect of these experiments is the presence of a bosonic isotope of lithium, lithium-7 (\(^7\)Li). The presence of the \(^7\)Li is essential for technical reasons that will be explained later, however, bosons have a distinctly different quantum mechanical behavior from fermions, and we can use the \(^7\)Li as probe, giving us more information about the fermions.

Since the experiments of this thesis focus on the differing quantum behavior we shall briefly review just what the conditions are for quantum degeneracy for both the boson, \(^7\)Li and the fermion, \(^6\)Li.

1.1 Quantum Degeneracy

When a sample of atoms is cooled to temperatures near absolute zero and densities near \(10^{12}\) atoms/cm\(^3\), the atoms quantum mechanical nature becomes apparent. This regime is known as quantum degeneracy. It is measured by a quantity called phase space density. It is determined by the atoms thermal de Broglie wavelength, \(\Lambda\), given by

\[
\Lambda = \sqrt{\frac{2\pi \hbar^2}{mk_B T}}
\]  

(1.1)
Figure 1.1 In the zero temperature limit particles following Bose statistics will pile into the lowest available energy state of the trap forming a Bose-Einstein condensate or BEC. Conversely, Fermi particles cooled to absolute zero will fill up the lowest available energy states with unity probability up to the Fermi energy.

and the density of the atoms. The phase space density, $\rho$ is given by

$$\rho = n \cdot \lambda^3$$

(1.2)

and when $\rho$ is approximately unity, then the atoms are said to be quantum degenerate. For the bosons this limit is characterized by a phase transition where all the atoms occupy the lowest energy level of the trap and form what is called a Bose Einstein Condensate, or BEC. Conversely, fermions simply fill up the lowest available energy levels of the trap with unity occupation. So rather than having the atoms pile into one state, the fermions experience a purely quantum force that excludes more then one of them from occupying a given energy level. Figure 1.1 shows pictorially this difference between quantum degenerate regime for bosons and fermions.

Since the focus of the thesis is on the observation of quantum degenerate fermions we will look at this regime a little closer.

1.1.1 Quantum Degenerate Fermions

Fermions become quantum degenerate at temperatures near 1 $\mu$K, similar to temperatures needed to form BEC. However, unlike BEC, Fermi degeneracy is not a critical phenomena. The temperature that characterizes Fermi degeneracy is $T_F$, the Fermi temperature. Since Fermi degeneracy is not critical phenomena, $T_F$ defines
the point at which the atoms start becoming quantum degenerate, as we will see in chapter 5. The Fermi temperature in a harmonic trap is given by:

$$T_F = \frac{\epsilon_F}{k_B} = \frac{\hbar \bar{\omega}}{k_B} (6N)^{1/3}$$

(1.3)

where $\bar{\omega}$ is the mean trapping frequency, and $N$ is the total number of fermions. So, with a million atoms in a trap, where $\bar{\omega} \approx 210Hz$, then $T_F \sim 1.8\mu K$. A more useful number is the ratio of the actual temperature $T$ to the Fermi temperature $T_F$. Then we can say that the atoms become quantum degenerate when $T/T_F = 1$ and they are completely quantum degenerate at $T/T_F = 0$.

### 1.2 Experimental Background

In order to study degenerate Fermi gasses one needs to produce a sample of fermion atoms at these ultra-cold temperatures. It turns out that are the current machinery that was developed to cool atoms for producing BECs fails to cool down a sample of fermions. Experimentalists currently employ a technique known as evaporative cooling [1] in order to atoms to these low temperatures. The idea is that the high temperature tail of gas in thermal equilibrium is forcibly removed. The gas re-thermalizes with a temperature less than the initial temperature since only the most energetic atoms were removed, and the process is repeated until the gas is at the desired temperature. The problem with this process is that is relies on the gas re-thermalizing through elastic atom-atom collisions, and at these temperatures quantum mechanics forbids elastic collisions between identical fermions.

However, quantum mechanics does not forbid elastic collisions between bosons and fermions. So we can use the evaporative cooling technique to cool the the bosons ($^7\text{Li}$) and use the bosons as a refrigerant to cool the fermions ($^6\text{Li}$) down to the same final temperature. And this is exactly what we have done, and it will be explained further in chapter 2.
1.3 Outline

This thesis will cover the experimental techniques implemented in order to achieve quantum degeneracy in a Bose \(^7\text{Li}\) Fermi \(^6\text{Li}\) mixture. We will first discuss the technique of Zeeman slowing, and how to construct a Zeeman slower. Next, in chapter 3, we will look at the procedures and timing involved in trapping and cooling lithium. Chapter 4 will cover the modifications made to the imaging system and the analysis needed to image these quantum degenerate clouds. Chapter 5 will then look at the exciting data detailing our observations of simultaneous trapping and cooling a sample of \(^7\text{Li}\) and \(^6\text{Li}\) to quantum degeneracy. Finally, we will conclude this thesis with a discussion of improvements and future experiments for this new apparatus.
Chapter 2
Zeeman Slowing

2.1 Background

The first step in cooling the atoms, called Zeeman slowing, works on the idea that light can be used to slow or cool atoms. When light interacts with matter, it can impart momentum to the matter. If a single photon is absorbed by an atom, that photon imparts momentum to that atom [2]. If the photon and the atom are travelling toward each other and undergo a head-on collision, then the momentum imparted to the atom will tend to slow the atom down. This is illustrated in figure 2.1, where a laser beam is incident onto a beam of atoms leaving an oven. The atoms absorb photons from the laser beam and feel an effective force opposing their motion, causing them to slow down. The momentum from one photon absorption is \( \hbar k \), where \( k \) is the photon wave vector. Then the average force felt by the atom is given by;

\[
F_{\text{average}} = \frac{\Delta_{\text{momentum}}}{\Delta_{\text{time}}} = \frac{1}{2} \hbar |k| \gamma
\]  

(2.1)

where \( \gamma \) is the lifetime of the excited state and the \( \frac{1}{2} \) is because the atoms can only absorb photons when the atoms are in the ground state [3], which is about \( \frac{1}{2} \) the time, for a laser intensity above the saturation intensity.

Up to this point we have only considered what happens with resonant light. However, as the frequency of the light is shifted away from resonance, the strength of the interaction rapidly decreases as \( \frac{1}{\Delta^2} \) where \( \Delta \) is the detuning of the laser from resonance. As the laser is detuned from resonance, the probability that the atom will absorb a photon decreases. This amazing sensitivity to the laser frequency allows us to manipulate the atoms with great precision, but causes problems when cooling a hot atomic beam because of the Doppler shift.

If atoms are moving towards a laser beam, there is a frequency shift of either the laser light (from the atom's point of view) or the atom's resonant frequency (as seen
in the laboratory frame), which is shown in figure 2.2. The Doppler shift is given by

\[ \nu = \nu_0 \frac{1 + \frac{V}{c}}{\sqrt{1 - \left(\frac{V}{c}\right)^2}} \]  

(2.2)

where \( V \) is the relative velocity between the atoms and the laser [4]. So, atoms coming out of the 800 K oven have an average Doppler shift of 1.45 GHz from their zero velocity resonance frequency. If we tune our laser to be resonant with the atoms emerging from the oven, then once the atoms slow their Doppler shift will decrease, they will fall out of resonance with the slowing laser and will no longer be cooled.

Zeeman slowing [5] circumvents this problem by tuning the transition frequency via the Zeeman effect. The Zeeman effect occurs when a magnetic field is applied to the atoms. The internal energy levels of the atom shift as \( \vec{p} \cdot \vec{B} \). The atoms can then be kept in resonance with the laser beam by applying a spatially varying magnetic field.

Figure 2.3 represents an energy level diagram for \(^7\text{Li}\). It shows how these levels change with an increasing magnetic field. The transition labelled 1 \( \leftrightarrow \) 2 is the cycling transition, and since the ground and excited states have different magnetic moments, the transition frequency, \( \nu_Z \), decreases as the magnetic field increases.

The objective behind using the Zeeman effect is to have a single laser beam in resonance with the atoms. Then as the atoms cool down, the Zeeman shift compen-

![Figure 2.1](image)

**Figure 2.1** For atoms leaving the oven and laser light travelling towards the oven, the atoms experience a net force resulting from the absorption and spontaneous emission of a photon.
Figure 2.2 When an atom is travelling toward a laser beam the the resonance frequency between a ground (g) and an excited (e) state is shifted by an amount delta (Δ), which depends on the velocity (V) of the atom.

\[ \text{7Li Zeeman Slowing Transition} \]

![Graph showing energy levels and transitions](image)

Figure 2.3 Zeeman levels for \(^7\text{Li}\). \(\nu_0\) is zero magnetic field separation of 803.5 MHz. The transition marked \(1\leftrightarrow2\) is the desired cooling transition. It is the \(\sigma^-\) transition. The \(m_i\) labels the nuclear spin, while the \(m_j\) labels the electronic spin. \(\nu_r\) is the re-pumping transition, and is needed to avoid optical pumping before the atoms enter the Zeeman slower. For clarity, only select levels of the \(2P_{3/2}\) are shown, and only select level labels are shown. For a full diagram see Ref. [6].
Tapered Solenoid

Figure 2.4 This is an illustration of how a Zeeman slower should work. The atoms enter a tube with an increasing magnetic field. A laser beam is applied from the opposite end of the tube, such that the atoms and the laser beam are travelling in opposite directions. As the laser beam cools the atoms, the increasing magnetic field compensates for the decreasing Doppler shift, thus keeping the atoms in resonance with the slowing laser. When the atoms reach the far end of the tube, they have been cooled.

states for the atoms decreasing Doppler shift. To accomplish this, we need to tailor a magnetic field so that it increases in such a way as to exactly counter the changing Doppler shift.

Figure 2.4 shows how this magnetic field can be produced. A tapered increasing magnetic solenoid is placed around the atoms. The slowing laser beam is tuned to be in resonance with the hottest atoms. Then as the atoms travel down the tube, they are cooled by the slowing laser beam. As they continue to travel down the tube, they experience the increasing magnetic field which keeps the atoms in resonance with the slowing laser so they can be cooled further.

This tube and solenoid arrangement is known as a Zeeman slower. The key behind the slower is matching the shape of the magnetic field to properly compensate for the decreasing Doppler shift in the atoms as they are cooled.

2.2 Design of a Zeeman Slower

As mentioned, the major principle behind Zeeman slowing is that the slowing laser frequency remains fixed while the magnetic field changes in such a way as to counteract the decreasing Doppler shift. To determine the necessary size and shape of the magnetic field needed for the Zeeman slower, the desired deceleration of the
atoms must first be determined.

The deceleration of the atoms is set by the amount of momentum imparted to an atom and how often the atom absorbs a photon. For this type of cooling the atoms absorb photons and then spontaneously decay back to the ground state. The minimum amount of time between absorbing a photon is given by the time needed to spontaneously emit the photon, which is the lifetime of the excited state. Further, the maximum change in velocity is due to the momentum kick of one photon. Putting this all together yields a maximum deceleration known as $a_{\text{Doppler}}$, which is just given by,

$$a_{\text{Doppler}} = \frac{\hbar \cdot k \cdot \gamma}{2 \cdot m}$$  \hspace{1cm} (2.3)

This is the maximum deceleration since it relies on the atom always being in resonance and always spontaneously emitting. So rather than being called a maximum, it should probably be called an ideal deceleration since it can not be attained in practice. As a result, we must choose a deceleration that is some fraction of $a_{\text{Doppler}}$ for our slower.

In the lab there have been two previous Zeeman slower designs; one with a deceleration of 0.5 $a_{\text{Doppler}}$ [6] and one with a deceleration of approximately 0.2 $a_{\text{Doppler}}$ [7]. Wishing to improve on the past designs, we chose a deceleration of $\sim 0.6a_{\text{Doppler}}$ for the new Zeeman slower design.

Now that we have chosen a deceleration of 0.6 $a_{\text{Doppler}}$, we can choose another parameter, the length of the Zeeman slower. The length of the Zeeman tube along with the deceleration of the atoms tells us the maximum velocity that the atoms can have and still be fully slowed. The length of the slower can be calculated from classical mechanics, such that the length of the slower, $z_0$, is given by

$$z_0 = \frac{V_0^2}{2 \cdot a} .$$  \hspace{1cm} (2.4)

where $a$ is the 0.6 $a_{\text{Doppler}}$, and $V_0$ is the maximum initial velocity for atoms in the Zeeman slower. Knowing $V_0$ can also give an estimate for the total cold atom flux
Figure 2.5 This shows the thermal distribution for atoms coming out of an 800 K lithium oven. The Zeeman slower length is chosen to maximize the number of atoms that can be slowed.

out of the Zeeman slower. Figure 2.5 shows the thermal distribution of the atoms emerging from an 800 K oven. All the atoms with initial velocities of $V_0$ or less are slowed by the Zeeman slower.

If we pick a length for the Zeeman slower we can then use equation 2.4 to find $V_0$ and use $V_0$ to determine the maximum magnetic field need. This is done by equating the Doppler shift from equation 2.2 with the Zeeman shift due to a magnetic field with strength $B_0$. If we look back at figure 2.3 and note that the frequency shifts like $-\mu_B B/\hbar$ [8], we find the peak magnetic field is given by

$$B_0 = \frac{\hbar \cdot k \cdot V_0}{\mu_B}. \quad (2.5)$$

We can use this same reasoning to determine the shape of the magnetic field. Since the laser detuning, $\Delta_L$, is set to the maximum Doppler shift, we can make an equality like equation 2.5 that is valid at every point in the Zeeman slower;

$$\Delta_L = -\mu_B \cdot B(z) - \hbar \cdot k \cdot V(z). \quad (2.6)$$

With a little algebra we can derive an equation for the magnetic field which depends
only on the position, \( z \), of the atoms in the slower;

\[
B(z) = B_0 \left[1 - (1 - z/z_0)^{\frac{1}{2}}\right] \tag{2.7}
\]

The final design criterion is simply to convert this magnetic field into current. This will give us a tangible experimental quantity for constructing the Zeeman slower. However, this is straight-forward since in a solenoid the magnetic field is proportional to the current, and we get \([6]\);

\[
i(z) = i_0(1 - (1 - z/z_0)^{\frac{1}{2}}) \tag{2.8}
\]

With equations 2.2 to 2.6 and equation 2.8 we have the theoretical tools needed to construct a Zeeman slower.

### 2.3 Constructing a Zeeman Slower

In order to construct the Zeeman slower we must use the equations from section 2.2 to determine the physical constraints. The primary consideration is \( B_0 \), the maximum magnetic field. We must make sure that \( B_0 \) remains experimentally attainable. Also, we must put some physical constraints on \( z_0 \), the length of the slower, so we do not end up having a Zeeman slower that will not fit in the lab. With these constraints in mind, we chose 760 Gauss field for \( B_0 \). This value for \( B_0 \) makes the full length of the slower less than 16 inches, using 0.6 \( a_{Doppler} \) for the deceleration. With these parameters, the total cold atom flux was calculated to be \( 10^{12} \text{ atoms/s} \) \([9]\).

Now we must generate the required magnetic field. We can approximate the required current given in equation 2.8 by creating bins with differing integer amounts of current. Figure 2.6 shows this current binning. We have divided the total current into 140 different bins, 70 10 amp bins in the main Zeeman coil, and 70 2 amp bins for the trim Zeeman coil. By making the bin size large enough for five turns of Belden 18 gauge wire, we can use the histogram as a guide for wrapping the Zeeman slower.
Figure 2.6  This shows how the Zeeman slower was wrapped. The calculated field was divided up into two increments, a 10 amp and a two amp. The slower is then wrapped with two coils, the mains and the trim. The mains are 10 amp/turn shown in / bars, and the solids bars are the 2amp/turn trim coils. This produces a maximum field of 756 G.

Further, knowing the number of turns and amount of current allows us to calculate the power requirements for the Zeeman slower.

The power requirement is another crucial concern since we do not want the Zeeman slower to burn up. This is exactly what would happen, since with the estimated current and number of wraps the slower would have to dissipate over 300 W. For this reason we construct the tube for the Zeeman slower following the design outlined in

Figure 2.7  This is a cross sectional view of the Zeeman slower design showing the double wall construction. Cooling water enters through a cooling port, is channelled down the slower, and then exits back out. (All dimensions are in inches.)
J. Tollett's Ph.D. thesis. That is a dual walled tube that allows for water to flow between the high vacuum and the Zeeman slower coils. This provides cooling for Zeeman slower and keeps the high vacuum tube from getting hot and outgassing [6]. A simplified machine drawing for the tube is shown in Figure 2.7. All the machine drawing are available on lab\cadd\emtrap\zeeman*.dwg, and in the apparatus II files, under Zeeman slower.

To help cool the coils further, the entire Zeeman slower is potted with a generic thermally conducting, but electrically insulating epoxy from the Newark corporation. It is a two part compound Styecast 2850-FT resin mixed with a generic Styecast catalyst. This black epoxy aids in the cooling the slower and also provides structural rigidity keeping the wires in place.

2.4 Results

Now that the Zeeman slower has been constructed, it can be tested. This first test is a bench test. We take an axial hall effect probe and map out the magnetic field from the solenoid. Figure 2.8 shows this data along with a comparison to our calculation. The sharp drop off in field at the high end is due to the insertion 1/2 inch mu-metal steel sandwich. This consists of five layers each 0.125 inches thick. First is the high permeability mu-metal, followed 304 stainless steel, then a low permeability mu-metal, another 304 stainless steel piece, and finally another high permeability mu-metal piece. This layering was found experimentally to produce the quickest falloff of the slower's magnetic field. We can take this same data and transform it into a plot of deceleration. This is shown in Figure 2.9, and agrees with our estimated deceleration of 0.6 $a_{doppler}$.

Once the hall probe confirms the slower is good, we want to see what the atoms think. To do this we will look at the cold atom flux into our MOT, which will be discussed in the next section. For this test, we used 90 mW in the Zeeman slower
Figure 2.8  Zeeman slower magnetic field. The solid curve is the calculated field profile. The closed circles are the measured Zeeman field with a flux return to minimize stray fields in the 2-D collimation MOT.

beam 1.421 GHz detuned from the $^7$Li $^2S_{1/2}$ F = 2 and 5 mW detuned 1.421 GHz from the $^7$Li $^2S_{1/2}$ F = 1. We then pass 10 amps through the main Zeeman coil and 2.0 amps through the trim coil. Figure 2.10 shows the florescence collected on a photo-detector from atoms captured in the MOT. The photo-detector is then calibrated [7] and we can convert this florescence into number of atoms [7]. With this information we can extract the MOT load rate, by looking at the initial slope of the curve in Figure 2.10. This show a load rate of about $5 \cdot 10^{10}$ atoms/s.

While this is a reasonable load rate, it is not the whole picture. The MOT trapping region sits over six inches from the end of the Zeeman slower, and as mentioned earlier, the Zeeman slower only slows the atoms in the direction of the laser beam. So when the atoms emerge from the slower, their forward motion is cold, but they have a lot of energy in other two dimensions, so the cold atom beam expands rapidly. To counteract this, there is a 2-D collimation MOT, which is discussed in detail in reference [7]. The 2-D MOT is very important, without the collimation, the load rate is near 100 times lower than what is shown in Figure 2.10. This is for two main
Figure 2.9  Zeeman deceleration. The solid line is the calculated zeeman deceleration due to the Zeeman slower field, assuming the optical transition is saturated.

Figure 2.10  Load rate for \(^7\)Li Zeeman slower. The graph shows photodiode signal verses time for a typical \(^7\)Li load rate. A measurement of the optical density gives \(\sim 2 \times 10^{10}\) atoms after loading, yielding a load rate of \(\sim 10^{10}\) atoms/s.
reasons; first is the collimation of the slowed beam, secondly, the Zeeman slower axis is offset from the MOT axis, so the thermal atomic beam does not pass through the MOT region, and the 2-D MOT helps push the slowed atoms into the center of the MOT.

Since we must collimate the output of the Zeeman slower to efficiently load the MOT, the MOT load rate is not a great measure of the cold atom flux from the Zeeman slower, but it is important parameter.
Chapter 3
Experimental Techniques

3.1 MOT
3.1.1 MOT Magnetic Fields

The first step in this experiment is to create a magneto-optical-trap or MOT of $^7$Li. The MOT is created using a anti-Hemholtz magnetic field and six counter-propagating laser beams.

The anti-Hemholtz magnetic field is created using a combination of the magnetic trap coils. The magnetic trap has three pairs of coils, the anti-bias coils, the curvature coils, and the quadrupole coils. Each set is named after the magnetic fields they form for the magnetic trap, which will be discussed in the next section. To generate the MOT magnetic field we use one anti-bias coil and one curvature coil, as depicted in figure 3.1. When 18 amps are passed through the coils in this configuration a 30 G/cm anti-Hemholtz field is produced. The actual current for the MOT is found by maximizing the MOT florescence and is 18 ± 2 amps. Since two coils with dissimilar radii are used to generate the MOT magnetic field, the zero of the anti-Hemholtz field sits roughly 1 mm out of the center of the trapping region, towards the curvature coil. The MOT is centered in the trapping region by applying a 3 G Hemholtz field. This field serves two purposes. First, the Hemholtz field centers the MOT in the trapping region. Secondly, it provides a constant magnetic bias field so the atoms can be optically pumped once the MOT fields are shutoff.

3.1.2 MOT Laser Setup

The MOT laser beams are produced from Coherent 699 ring dye laser. The main laser frequency is set 6 $\Gamma$ from the $^7$Li $^2S_{1/2}$ F = 2 $\leftrightarrow$ $^2P_{3/2}$ transition. (See figure 3.3.) This laser light provides the main trapping or cycling transition for the MOT.
Figure 3.1 The MOT magnetic field is generated by energizing one anti-bias coil and one curvature coil. At 18 amps, these coils produce a 30 G/cm field. However since the coils are slightly different sizes, the magnetic zero sits about 1mm closer to the curvature coil.

However, the $^{2}\text{P}_{3/2}$ $m_F$ levels are only split 18.1 MHz. This causes atoms in the $^{2}\text{S}_{1/2}$ $F = 2$, $m_F = 2 \leftrightarrow ^{2}\text{P}_{3/2}$ $F = 2$, $m_F = 3$ transition to fall into $^{2}\text{S}_{1/2}$ $F = 1$, $m_F = 1$ state, and be lost from the trapping transition. To circumvent this loss, a re-pumping laser beam is required in MOT configuration. The re-pump laser beam is generated by an 812 MHz electro-optical modulator, or EO, which is 6 $\Gamma$ red of the $^{7}\text{Li}$ $^{2}\text{S}_{1/2}$ $F = 1 \leftrightarrow ^{2}\text{P}_{3/2}$ transition. The RF drive power on the EO is set such that there is $\sim 46\%$ $F = 2$ light and $27\%$ $F = 1$ light and 27% in an unused sideband. The total laser power for all six beams is $\sim 120$ mW with a 1.75 cm $1/e^2$ waist, aperture to $\sim 1.25$ cm. The Zeeman slower, as described in chapter 2, uses $\sim 90$ mW of power detuned 1.25 GHz blue of $^{2}\text{S}_{1/2}$ $F = 2 \leftrightarrow ^{2}\text{P}_{3/2}$ transition with $\sim 5$ mW re-pumping light detuned 1.421 GHz blue from the $^{2}\text{S}_{1/2}$ $F = 1 \leftrightarrow ^{2}\text{P}_{3/2}$ transition. Further, the 2-D MOT uses 40 mW of laser power, and has a $1/e^2$ waist of 0.75cm. With this combination, and the oven at 500 °C, we are able to attain a load rate of $\sim 1 \cdot 10^{10}$ atoms/second into the MOT, as seen in figure 2.10. The MOT is typically loaded for 2 to 5 seconds. When the MOT is fully loaded it is roughly 1.5cm in diameter, over
Figure 3.2 This diagram shows the frequency generation for the $^7\text{Li}$ MOT. The dye laser typically outputs 800 mW. This allows us to achieve 120 mW in the trapping beams, 40 mW in the 2-D MOT, 90 mW in the Zeeman slower, and 250 mW in the optical pumping beam.

Figure 3.3 This shows the relevant energy levels of both $^6\text{Li}$ and $^7\text{Li}$. The arrows indicate the trapping and re-pumping transitions.
Figure 3.4  This figure shows the optical setup for an electronically tunable FM absorption lock. The FM absorption lock is identical to that described in reference [11], with one exception. A second A.O. is double passed. The output of the double passed A.O. can be scanned ± 40 MHz without miss-aligning the lock. This allows the laser frequency to be tuned by scanning the lock.

a factor of 10 larger than typical MOTs [3], due to the large number of atoms loaded [10].

3.2 DUAL MOT

Once the $^7$Li has been loaded into the MOT, we are now ready to load the $^6$Li. The $^6$Li MOT is created using 180 mW from the Spectra 380D dye laser locked to the $^6$Li $^2S_{1/2}$, $F = 3/2 \leftrightarrow ^2P_{3/2}$ crossover. The laser light for the lock is shifted 150 MHz blue, using a double pass AO at 75 MHz. This lock set up puts the main trapping frequency 36 MHz ($6\Gamma$) red of the $^2S_{1/2}$, $F = 3/2$, $m_F = 3/2 \leftrightarrow ^2P_{3/2}$ F = 3/2, $m_F$ = 5/2 transition. The re-pump frequency is 6 $\Gamma$ red of the $^2S_{1/2}$, $F = 1/2$, $m_F = 1/2 \leftrightarrow ^2P_{3/2}$, and is generated using a 228 MHz AO. The laser beams are combined onto a 70/30 beam splitter and 70% of F = 3/2 and 30% of F = 1/2 light is then coupled into a single mode optical fiber (Thorlabs FS-SN-3224 4.0 $\mu$m single mode optical
Figure 3.5 Laser beam layout for the $^6$Li MOT. The beam is generated from a dye laser, a small portion of the beam locks the laser frequency. Another 4% is removed for the absorption probe beam. The rest of the beam then forms the MOT and 2-D MOT. They are both switched on and off by a 40 MHz switching AO.

fiber). The output of the optical fiber is collimated to a $1/e^2$ waist of 1.25 cm with typical powers of 28 mW in the $F = 3/2$ and 12 mW in the $F = 1/2$. The beams are then overlapped with the $^7$Li MOT onto a polarizing beam splitter. The remaining beam with 30% $F = 3/2$ and 70% $F = 1/2$ is collimated to a $1/e^2$ waist of 0.75 cm and used for the 2-D collimation MOT. The Zeeman slower light is generated by an injection locked master/slave diode system, see figure 3.6, which provides 30 mW, 1.4 GHz blue of the $F = 3/2$ transition. With this setup we obtain a load rate of $\sim 1\times 10^9$ atoms/second and we can load for $\sim 10$ s and achieve $10^{10}$ atoms. However, in practice the $^6$MOT is only loaded for 3 - 30 ms.

The load time of the $^6$Li is reduced for two main reasons: The first reason is straightforward, since we are not evaporating the $^6$Li there is no need to start with so many atoms. In fact, since the sympathetic cooling ceases roughly where the number of the $^6$Li atoms exceed the number of $^7$Li atoms, we purposefully load only about $10^6$ $^6$Li atoms to have good sympathetic cooling down to quantum degenerate temperatures. The second and most important reason for limiting the $^6$Li load time
Figure 3.6  This figure shows the setup for the master slave diode system used for the $^6$Li Zeeman slower. A nominally 10 mW external grating laser injection locks a 30 mW slave laser, allowing the full 30 mW to be used.

Figure 3.7  The $^6$Li D2 lines are shown with respect to the $^7$Li D1 $F = 2$ transitions. The figure shows that for a red detuned $^6$Li MOT the $^6$Li D2 $F = 1/2$ light will be nearly in resonance with the $^7$Li D1 $F = 2, F' = 1$ transition. This overlap in frequencies destroys the $^7$Li MOT.
is because the $^6$Li MOT hurts the $^7$Li MOT. The reason for this can be seen in Figure 3.7. The $F = 1/2$ transition in $^6$Li is very close to the $^7$Li D1 $^2S_{1/2}$ $F = 1 \Leftrightarrow ^2S_{1/2}$ $F = 2$. In normal MOT mode, the $^6$Li $F = 1/2$ light is detuned red by 6 $\Gamma$, which puts the frequency $\sim 1$ $\Gamma$ blue of the $^7$Li D1 $^2S_{1/2}$ $F = 1$. The presence of the $^6$Li light reduces the fluorescence signal from the $^7$Li MOT by over a factor of five. Further, visual inspection of the $^7$Li shows that the center portion of the MOT is blown out by the $^6$Li light. If the $^6$Li MOT frequencies are detuned less than 6 $\Gamma$ the $^7$Li MOT fluorescence signal is still suppressed, however, the shape of the $^7$Li MOT changes from having a hole in the middle to being just the central core with the exterior blown away. As the $^6$Li light is detuned further than 6 $\Gamma$, the detrimental effects on the $^7$Li MOT diminish, however, at these large detunings, greater than $\sim 6.5$ $\Gamma$, we are unable to load a significant amount of $^6$Li into the MOT. Therefore, in order to minimize the impact on the $^7$Li MOT, we only pulse the $^6$Li MOT laser light on for between 3 ms and 30 ms, providing us with between $10^6$ and $10^7$ $^6$Li atoms.

3.3 Loading the Magnetic Trap

3.3.1 Loading $^7$Li into the Magnetic Trap

Our goal with the $^7$Li is to transfer the maximum number of atoms from the MOT to the magnetic trap at the coldest temperature possible. To this end we have developed a several step process in which we cool, compress, and optically pump the the atoms in order to maximize the transfer to the magnetic trap. This ramp, as it is known, is quite sensitive to its parameters, and the parameters can vary depending on laser intensities, the amount of atoms in the MOT, and the size of the error signal which locks the laser to the appropriate transition. Figure 3.8 shows an overview of the timing of the magnetic and optical fields needed to transfer the atoms from the MOT to the magnetic trap.

The specific steps used in loading the trap are as follows: We first close the
Figure 3.8  This figure shows the general timing of the magnetic fields and light for transferring atoms from the MOT to the magnetic trap.
Zeeman shutter to stop the MOT loading, then 30 ms later we compress the MOT by reducing the amount of $F = 1$ light by a factor of 100, forming a temporal dark spot MOT. This works on the premise that by lowering the re-pump intensity the atoms will spend more time in the $F = 1$ state and since they are seeing less of the $F = 1$ light, the re-radiative density limiting forces in the MOT will decrease, allowing the density of the atoms in the $F = 1$ state to increase, thereby compressing the MOT; [10]. However, since the re-pump light has been reduced, the trapping force of the MOT has decreased, which is why the dark spot must be temporary [10]. If this condition is kept too long we lose atoms from the MOT. Now that the MOT is compressed, we move the laser detuning from 6 $\Gamma$ to a detuning set by a parameter called det.cool, in order to cool the atoms. The value of det.cool is typically 2 $\Gamma$ but it can vary $\pm 0.5 \Gamma$. We then wait 6 ms for the Coherent dye laser to respond and for the laser frequency to actually change. Once the frequency has changed, we ramp the MOT intensity down from full power to a level set by the mot.off parameter, which is typically 10% of the full intensity. This combination of ramping the frequency and lowering the laser beam intensity cools the MOT down from 1 mK to 750 $\mu$K.

Now that the MOT has been cooled and compressed we are left with one problem. The compression stage puts the majority of the atoms into the $F = 1$ manifold, and we want the atoms to be in the $F = 2, m_F = 2$ state. The next step is to optically pump the atoms into the $F = 2$ manifold. We turn off the MOT magnetic field so that we only have a well defined 3 G bias field from our external centering cage. We then drive the 812 MHz EO in order to completely suppress the carrier. The laser beam then contains 20% $F = 1$ light and 80% in unused sidebands. The laser is then pulsed on in MOT configuration for 200$\mu$s to pump the atoms into the $F = 2$ manifold.

In the $F = 2$ manifold there are five $m_F$ levels, so with no further optical pumping there would only be 1/5 of the atoms in the desired state. In order to avoid this loss,
we apply a $m_F$ optical pump pulse. This consists of two circular polarized counter propagating beams along the bias field axis with an even mixture of $F = 2$ and $F = 1$, light each red detuned 35 $\Gamma$ from the $^2S_{1/2} F = 2$, $m_F = 2 \leftrightarrow ^2P_{3/2} F = 2$, $m_F = 3$ transition. The beam has a $1/e^2$ waist of 1 cm and typically contains about 200 mW of optical power. The $m_F$ optical pump pulse duration is determined by a parameter called $plen$, which is typically 800 $\mu$s but can vary 50% depending on the optical pump pulse intensity, alignment, and spatial profile.

We now energize the magnetic trap. This is done similarly to the process described in McAlexander's thesis. The trap is energized so that its radial size matches the radial extent of the MOT. This is achieved by shunting current around the anti-bias coils as explained by McAlexander [7]. Typically there are about $3 \times 10^9$ $^7$Li atoms in the $F = 2$ $m_F = 2$ state transferred at a temperature of 750 $\mu$K. Some residual $^7$Li $F = 2$, $m_F = 1$ state is also trapped because of imperfect optical pumping. However spin exchange loss between the $F = 2$, $m_F = 1$ on itself eject this unwanted state from the trap [7].

### 3.3.2 Loading $^6$Li and $^7$Li into the Magnetic Trap

Efficient transfer of the $^6$Li into the magnetic trap is not important because we do not need much $^6$Li. However, we must consider what the $^6$Li light does to the $^7$Li atoms. For instance the $^6$Li $F = 1/2$ light that hurts the $^7$Li MOT can make the compression, the cooling, or the optical pumping fail. Further, since we make the normal $^6$Li MOT with very little power in the $F = 1/2$ frequency, the majority of the $^6$Li are in the $F = 1/2$ state and we want to catch the $F = 3/2$ $m_F = 3/2$ state in the magnetic trap. Therefore, we must transfer the $^6$Li in such a fashion as to have it in the desired state while not killing the transfer of the $^7$Li.

To minimize the damage of the $F = 1/2$ frequency on the $^7$Li MOT, we reduce the $F = 1/2$ light intensity by a factor of 10 immediately after loading the $^6$Li MOT. This
forms a temporal dark spot MOT for the $^6$Li and minimizes the amount of the F = 1/2 light present. Then, just before the $^7$Li is optically pumped into the F = 2 state, the $^6$Li light is turned off in such a fashion that the F = 3/2 MOT light shuts off 250 µs before the F = 1/2 light, providing an optical pump into the F = 3/2 manifold. It was found that if the $^6$Li light is present during the $^7$Li optical pump pulses, the amount of $^7$Li transferred into the magnetic trap was significantly reduced. With these modifications and a $^6$Li load time of about 10 ms, we are able to load about $3 \times 10^9$ $^7$Li atoms and $10^6$ $^6$Li atoms at a temperature of approximately 750 µK into the magnetic trap.

3.4 Evaporative Cooling

In our implementation of evaporative cooling, the atoms are forcibly removed from the trap by driving an RF transition between a trapped and an untrapped state in $^7$Li. Specifically, we drive atoms from the $^7$Li F = 2, $m_F = 2$ (2,2) state to the F = 1, $m_F = 1$ (1,1) state using microwave sweep between 915 MHz and 807 MHz. The atoms in the 1,1 state are anti-trapped so the magnetic trapping field rapidly ejects the 1,1 atoms from the trapping region. Then the remaining 2,2 atoms rethermalize with a cross-section of $8 \cdot \pi \cdot a^2$ where $a = -27.6 \ a_0$ [12] and the gas cools down. Once again the exact details of the evaporation are described in McAlexander's thesis. His thesis also contains information for creating optimized evaporation trajectories for a cloverleaf-type trap.

The current code for making an optimized trajectory is located in `/lab/source/iancode`. The main file, `evap.h` must be modified to change the bias field. If the file is modified, it must be recompiled using `make -f makeopt`. This makes an executable opt which has the following usage; `opt initialnumber finalnumber initialtemperature 200 filename -b backgroundlifetime`. This produces a file named `filename.dat` which contains six columns: time in seconds, number, temperature in µK, density, effi-
Figure 3.9  This figure shows a typical evaporation trajectory for the emtrap. The trajectory is an optimized evaporation modelled after Sackett’s optimization [13]. The optimization assumes $3 \times 10^9$ atoms at an initial temperature of 750 \( \mu \)K in a 3.2 G bias field. The efficiency factor, and \( \log(n_o\lambda^3) \). The file can be converted into a trajectory by running \textit{evaptraj}. The input is \textit{evaptraj filename.dat filename.in}. It creates the file \textit{filename.in} which \textit{ACK} reads for the evaporation. One further modification is made at this point; the evaporation trajectory is cropped to put the initial cut at 2 mK. This is done because the apparatus windows limit the axial trap depth to 2 mK, removing all the atoms with temperatures of 2 mK and above. Further, if the trajectories are not cropped, for some trajectories, the razor can spend up to 10 s slowly evaporating temperature above 2 mK. Our standard trajectory is shown in figure 3.9.

3.5 Sympathetic Cooling

As explained before, we evaporatively cool the $^7$Li and use it as a refrigerant to $^6$Li cool. The $^7$Li is evaporated using optimized trajectories [7, 13] meanwhile sympathetic collisions cool the $^6$Li. With this technique, temperatures as low as 250
nK are achieved.

In a typical optimized evaporation, the trajectory speeds up at the end to minimize the effects of dipolar loss collisions [14]. As the trajectory speeds up, however, the dual species gas has problems cooling. This was circumvented by slowing the last portion of the evaporation ad hoc and monitoring the lowest attainable temperatures. We found that the final two seconds of a trajectory optimized for for $3 \cdot 10^9$ atoms in a 3.0 G bias field had to be slowed by a factor of four to allow both isotopes to be cooled down to $\sim 250$ nK, which corresponds to 0.25 of the Fermi degeneracy temperature ($T_F$). Although the experiment was not done exhaustively, 0.25 $T_F$ appeared to be the lowest temperature we could achieve.

In order to explain this limiting temperature, we looked at the heat capacity of each gas. By a simple thermodynamic argument, if the Bose gas has less heat capacity than the Fermi gas, sympathetic cooling will break down. The heat capacity, $C$, is given by:

$$C = \frac{dE}{dT}.$$  

(3.1)

The heat capacity for an ideal, harmonically confined, Bose gas, at the critical temperature for BEC, is [15]:

$$C_B = 10.86 \cdot N_B \cdot k_B$$  

(3.2)

while for a Fermi gas at $T < T_F$ [16]

$$C_F = \pi^2 \cdot N_F \cdot k_B \cdot (T/T_F)$$  

(3.3)

where $N_B$ and $N_F$ are the number of bosons and fermions respectively. The respective numbers of bosons and fermions can be calculated for a harmonic trap with mean frequencies $\omega_7$ for bosons and $\omega_6$ for the fermions;

$$N_B = 1.202 \cdot \left(\frac{k_B \cdot T_C}{\hbar \cdot \omega_7}\right)^3$$  

(3.4)

$$N_F = \frac{1}{6} \cdot \left(\frac{k_B \cdot T_F}{\hbar \cdot \omega_6}\right)^3.$$  

(3.5)
The trap frequencies are related by

$$\omega_6 = \omega_1 \cdot \sqrt{\frac{7}{6}},$$

(3.6)

We assume that $T = T_C$ in equation 3.3, because we have a negative scattering length which limits the condensate number and keeps the gas at $T = T_C$. So, we can put $T = T_C$ into equation 3.2 for $C_B$. Then, setting $C_B = C_F$ gives an approximate limit for sympathetic cooling, since once $C_B < C_F$ the fermions will heat the bosons more than the bosons will cool the fermions. So if we set $C_B = C_F$ we find that

$$\frac{T}{T_F} \approx 0.28.$$  

(3.7)

One might assume that this limit could be overcome with a positive scattering length condensate and/or more atoms. Figure 3.10 shows the per particle heat capacity for bosons and fermions. As the bosons condense to zero temperature, their heat capacity goes to zero. So, if we had a positive scattering length condensate, the limit from Eq. 3.7 would still hold since the condensate fraction does not contribute to the heat capacity. Further, figure 3.11 shows plots of the total heat capacities for both the bosons and fermions as a function of number. The heat capacity of the bosons grows until the critical temperature is achieved and then its heat capacity plateaus at the value given by equation 3.2. This is because any additional atoms go directly into the condensate and do not contribute to the heat capacity, once again showing the limit of Eq. 3.7 holds.

Although this gives a limit for sympathetic cooling, it is not a hard limit. This is simply the point at which sympathetic cooling becomes inefficient. In fact, as shown in chapter 5, our data is consistent with this interpretation and we have been able to achieve $0.25 \ T/T_F$ thus far. Further, there are other methods and ideas that can be employed at this point in the experiment to obtain more degenerate Fermi clouds, such as simultaneous evaporation of the bosons and fermions.
Figure 3.10  This figure shows the per-particle heat capacity for bosons and fermions near $T = 0$. The bosons are shown in the dotted line, while the fermions are the solid line. Taking the point at which their heat capacities are equal to be the limit of sympathetic cooling, give $T/T_F = 0.28$.

Figure 3.11  This figure shows the heat capacities for bosons and fermions around $T = T_C$. The plots show the limit of sympathetic cooling and demonstrates that adding more bosons does not affect the limit.
Chapter 4
Imaging

4.1 Imaging System

The data in these experiments was collected using near resonance absorption imaging. The imaging system consists of a 1.6X custom compound microscope described in McAlexander's PhD thesis [7]. The image is then magnified by an Mitutoyo BD Plan Apo 10X infinite conjugate microscope objective and imaged onto a Photometrics liquid cooled CCD array using a commercial NIKON 75-240mmf/4.5-5.6 "D" AF zoom lens. The combination of the zoom lens and microscope objective allows us to easily change the magnification from 5.5 to 19 without refocusing the imaging system. Further, as described by McAlexander, the compound lens sits inside a re-entrant port, giving an f number of ~3.2 [7].

The $^7$Li imaging is done with a 6 $\mu$s pulse of $F = 2$ light, which is delivered to the experiment through a single mode optical fiber. The fiber's output is collimated to a 0.87 mm 1/e$^2$ waist using an Optics For Research Vari-Focus ® lens. A Thorlabs FPC-030 optical fiber polarization controller sets the probe polarization perpendicular to the bias field. The probe light is shuttered using a 2 mm open aperture, 100 $\mu$s rise time, Uniblitz LS2Z2 shutter. The detuning of the probe light can be tuned by the computer, from 0 $\Gamma$ to 8 $\Gamma$ by varying the parameter absdetune from 0.0 to 0.6.

Difficulties with imaging arise from three main areas, uncertainty in the detuning, optical pumping, and spatial noise on the probe beam. The uncertainty in the detuning is due to the finite resolution of the lock signal used to lock the laser frequency to the $^2S_{1/2}$ F = 2 $\leftrightarrow$ $^2P_{3/2}$ F = 3 transition in $^7$Li. The uncertainty in the probe detuning is ±3 MHz (0.5 $\Gamma$) and it effect is minimized by detuning as far from resonance as possible, up to 7 $\Gamma$. The problem of optical pumping comes from the relatively small separation of the excited state hyperfine levels in lithium (see
Figure 4.1  This diagrams the process of absorption imaging. The probe beam is incident on the atom cloud and the cloud creates a shadow in the beam. The shadow is then collected with the imaging system and a combination of the imaging systems magnification and the setting of the zoom lens sets the overall magnification. The zoom lens allows the magnification to be varied between $x5.5$ and $x19$.

Figure 3.3). Since the spacing of the excited state hyperfine levels is only $3 \, \Gamma$, as we detune from resonance the relative detuning from transitions other than from the 2,2 transition becomes negligible and the cycling transition is lost. To overcome this problem we would like to image the atoms with light that is circularly polarized along the quantization axis, or $\sigma^+$ light, in order to only drive only the cycling transition. However, the geometry of our imaging system prevents this, so we use light that is linearly polarized perpendicular to the quantization axis to simulate an even mixture of $\sigma^+$ and $\sigma^-$ light. Although this does a good job, it is not perfect and we require the trap to be energized in order to have a well defined quantization axis. Further, we flash on all 6 MOT beams for 6 $\mu$s, simultaneous with the probe light, with 60 mW of $F = 1$ light present to re-pump any atoms lost from the cycling transition.

The final problem of beam noise can be nearly eliminated by normalizing out the shape of a beam with atoms to a beam without atoms. However this is not perfect and does not remove all the noise from the signal. We are currently attempting to
**Figure 4.2** This figure shows the measured axial and radial trapping frequencies for the EM Trap. The measurement was made by applying a weak oscillating magnetic field to the trapping region during an evaporation cycle halting at 2 $\mu$K. Plotted is the percent absorption vs RF drive frequency.

clean up the spatial beam noise by improving the optical fiber collimation optics.

The magnification of the imaging system has been measured both piecewise on the bench by imaging a Mellis Griot USAF 1965 test target, and in situ using a beam that is focused at the position of the atoms which can be translated to measure the magnification. The bench test target and the in situ measurement gave the magnification to be $7.6 \pm 0.16$. Further, we have measured both the axial and radial trapping frequencies at 1.5 G bias field to be 39 Hz axially and 433 Hz radially, see figure 4.2.

Combining this information we can extract the temperature from simple Gaussian fits using the equation

$$k_B \cdot T = \frac{1}{2} \omega^2 r^2$$  \hspace{1cm} (4.1)

for classical regime. However, we are only able to image clouds colder than 6 $\mu$K due to the high magnification of our imaging system.

At temperatures below 2 $\mu$K the data is fit using either a Bose-Einstein distribution for the $^7$Li or a Fermi-Dirac distribution for the $^6$Li, which will be discussed in section 4.3.
4.2 Dual Imaging

The $^6\text{Li}$ is imaged in the same manner as the $^7\text{Li}$. The $^6\text{Li}$ laser light is locked to the $^6\text{Li} \ ^2\text{S}_{1/2} \ F = 3/2 \leftrightarrow ^2\text{P}_{3/2}, \ m_F = 5/2$ transition, and overlapped on a 50/50 beam splitter with the $^7\text{Li}$ probe light. Both beams then go through a 40 MHz AO and are coupled into the same optical fiber. This allows both beams to be spatially overlapped with the same polarization and beam waist.

Each laser has a beam dump shutter which completely blocks the lasers during the evaporation cycle. Therefore, in order to individually probe one isotope at a time, we simply open the $^7\text{Li}$ shutter, probe the $^7\text{Li}$ with a 6 $\mu$s pulse then apply a 20 $\mu$s on-axis pulse to remove any remaining $^7\text{Li}$ atoms. We then close the beam dump shutter for the $^7\text{Li}$, open the $^6\text{Li}$ beam dump shutter, and probe the $^6\text{Li}$ with a 6 $\mu$s pulse.

4.3 Image Analysis

The image analysis is done using a graphically interfaced MATLAB program written by A. G. Truscott. Similar to the existing software for the permanent magnet experiment, the user selects a region for the center of the cloud. The program then finds the major axis of the cloud and averages a $+/–5^\circ$ angle about the axis. The entire image is not used to eliminate error from image distortions along the tight axis. Then both a classical Gaussian fit and a quantum Bose-Einstein or Fermi-Dirac fit is performed. The results of the Gaussian fit are then used as initial guesses quantum distribution fits. The raw data and both fits, along with the temperature, number, density, and phase space density are displayed. The uncertainties in our measurement on number and temperature are convolved since the shape of the Bose gas changes with number and temperature. To estimate the uncertainties we calculate the reduced-$\chi^2$ values, and then vary the parameters to find the point at which the reduced-$\chi^2$ increases by 20%. The typical value for a reduced-$\chi^2$ from our data is 1.0.
This leads to resulting uncertainties of 8% in temperature and 15% in number [17]. These are the largest uncertainties.

4.3.1 Bose Clouds

The Bose clouds are fit to density distributions of the type presented by Bagnato et al. [15]. But before the distribution can be calculated we must first find the chemical potential $\mu$. The chemical potential is simply the change in energy for a given change in particle number, at a constant temperature. The chemical potential is implicitly related to the total number of particles through the relation; [18]

$$N = \sum_{n=1}^{n_{\text{max}}} \frac{g_n}{e^{\frac{E_n - \mu}{kT}} - 1}. \quad (4.2)$$

Here $g_n$ is the degeneracy factor, which is the number of states available states in the trap. For a symmetric harmonic trap the degeneracy factor can be written as:

$$g_n = \frac{(n - 1) + 2) \cdot ((n - 1) + 1)}{2} \quad (4.3)$$

The $E$ in equation 4.2 is the energy of the gas, and is given by;

$$E_n = \frac{3}{2} \hbar \cdot \omega (n + 1). \quad (4.4)$$

The chemical potential is found iteratively using equations 4.2-4.4.

Now that we have a chemical potential, we can calculate the optical density distribution. We use the method presented in reference [11] and reference [15] where a series expansion for the density distribution of a harmonically trapped Bose gas is calculated. The series expansion for the density distribution of the non-condensed atoms is

$$n(r) = \frac{1}{\Lambda^3} \sum_{t=1}^{t_{\text{max}}} \frac{e^{-\frac{E(r)}{kT}}}{t^3}. \quad (4.5)$$

Using equation 4.5 and the chemical potential found in equation 4.2 we can calculate a density distribution.
4.3.2 Fermi Clouds

The treatment of the Fermi gas is nearly identical to the treatment of the Bose gas, just some of the equations are modified to account for the difference in statistics. In particular the formulas for the chemical potential and the density distribution must be modified to comply with Fermi statistics. Equation 4.2 is slightly modified to

\[
N = \sum_{n=1}^{n_{\text{max}}} \frac{g}{e^{\frac{E_n}{T}} + 1},
\]

(4.6)

where the only change is the sign in the denominator. In order to calculate the density distribution we must also modify the form of the sum. In the Bose case the sum comes from the binomial expansion of

\[
\frac{1}{e^z - 1} = \sum_{n=1}^{\infty} e^{(-n \cdot z)}.
\]

(4.7)

With the Fermi distribution the new expansion becomes

\[
\frac{1}{e^z + 1} = \sum_{n=1}^{\infty} (-1)^{n-1} e^{(-n \cdot z)}.
\]

(4.8)

Expansion 4.8 can be substituted into equation 4.5 rather than using the Bose expansion from equation 4.7, yielding a Fermi density distribution given by

\[
n(r) = \frac{1}{\Lambda^3} \sum_{l=1}^{l_{\text{max}}} (-1)^{l-1} \cdot \frac{e^{c \cdot \frac{\mu - E(r)}{kT}}}{l^{\frac{3}{2}}}.
\]

(4.9)

4.3.3 Optical Density

In order to compare the generated density distributions to our data, the density distributions must be converted into optical density distributions. The optical density is given by

\[
\alpha(x, y) = \sigma \cdot \int dz \cdot n(x, y, z),
\]

(4.10)
where $\sigma_l$ is the light scattering cross-section, and $z$ is the spatial coordinate parallel with the probe beam. For a classical distribution the optical density has the form,

$$\alpha(x, y) = \sigma_l \cdot \int dz \cdot e^{-\frac{m_0 c^2}{\pi kT} (x^2 + y^2 + z^2)}.$$  \hspace{1cm} (4.11)

Here the $z$ integral can be carried out independently of the $(x, y)$ coordinates. The resulting distribution is a Gaussian in the $(x, y)$ plane, scaled by the peak optical density from the $z$ integration.

For a Fermi gas, the optical density can be found by integrating equation 4.9 over the $z$ coordinate. The optical density has the form,

$$\alpha(x, y) = \frac{\sigma_l}{\Lambda^3} \cdot \int dz \cdot \sum_{t=1}^{t_{max}} -1^{(t-1)} \cdot \frac{e^{\frac{\mu - (m_0 c^2/\pi kT)(x^2 + y^2 + z^2)}{t^2}}}{t^2}. \hspace{1cm} (4.12)$$

If we now write out the first two terms of the sum,

$$\alpha(x, y) = \frac{\sigma_l}{\Lambda^3} \cdot \int dz \cdot e^{\frac{-m_0 c^2}{\pi kT} (x^2 + y^2 + z^2)} - \int dz \cdot \frac{e^{2\mu - m_0 c^2 (x^2 + y^2 + z^2)}}{2^3} + \ldots \hspace{1cm} (4.13)$$

each term can be easily integrated, and the optical density is given by the sum of these terms. The process holds for the Bose case with the substitution of equation 4.5 for equation 4.9 in the above argument.

The problem with forming these optical density distributions, in this manner, is that it is computationally difficult, since around 10,000 terms are needed to form a good optical density distribution. Further, until the atoms are highly quantum degenerate, where $T/T_F \ll 1$ and $T \simeq T_c$, the density distributions are roughly classical. For this reason the data that is presented in chapter 5 are fit optical density distribution that are either Bose or Fermi density distribution in the $(x, y)$ plane and Gaussian in the $z$ plane. This semi-classical approximation allows the optical density distributions to be generated by scaling the Bose or Fermi density distributions by the peak optical density along the $z$ axis. The error in this approximation was estimated by doing the full integration of equation 4.13 for Fermi clouds near $T = T_F$ and at
$T/T_F = 0.25$. At higher temperatures the error in this method was negligible, and less than 2% at $T/T_F = 0.25$. In order to properly analyze clouds much colder than $T/T_F = 0.25$, the optical density must be calculated according to equation 4.13.
Chapter 5
Results

There are three main results from the present set of experiments. First is the observation of a Bose gas evaporatively cooled to quantum degeneracy. Second is the observation of a magnetically trapped Bose/Fermi mixture and the third is the subsequent simultaneous observation of a quantum degenerate Bose/Fermi mixture.

5.1 Evaporative Cooling of $^7$Li

The observation of a quantum degenerate Bose gas is mostly discussed in McAlexander’s PhD thesis, although, we had yet achieved quantum degeneracy at the time of his thesis. Further, since we are using $^7$Li in the F = 2, $m_F = 2$ state and imaging using near resonance absorption imaging we are unable to observe a BEC. This is due to the attractive scattering length in the F = 2, $m_F = 2$ state. The attractive scattering length limits the maximum condensate number to around 1000 atoms [11]. Due to this small number of expected condensate atoms and an estimated $1/e^2$ radius of the condensate is $< 3 \, \mu m$ [11], and due to our typical magnification of 5.5 $\mu m$/pixel we have not yet observed a 2,2 condensate. Figure 5.1 shows an axial cross section of an evaporatively cooled Bose cloud. The horizontal axis has a scale of 5.5 $\mu m$/pixel. The total number is 41,500, the temperature is 300 nK, yielding a peak phase space density of $\sim 2.6$. Comparing this to the permanent magnet experiment, and to the critical phase space density for BEC formation, which is 2.612 [19], implies that we have satisfied the conditions for forming a quantum degenerate Bose gas, even though we have not yet observe a BEC.
Figure 5.1  This is a cross sectional plot of a quantum degenerate $^7\text{Li}$ cloud. The fit is to a BE density distribution and gives a temperature of 300 nK and a number of 41,500 and a density of $1.6 \times 10^{12}$ cm$^{-3}$. This corresponds to a temperature of $T/T_c = 1.0$.

5.2 Dual Magnetic Trapping

The first observations of magnetic trapping of a $^7\text{Li}/^6\text{Li}$ mixture came in the form of lifetime measurements. To take a lifetime, we monitored a normalized fluorescence signal collected onto an 8-bit CCD camera as a function of time. Figure 5.2 shows a typical lifetime measurement. The fast decay is due to spin exchange decay, which is discussed in great detail in McAlexander's thesis. The main principle behind spin exchange collisions is that two atoms can individually change spin states while preserving the total spin projection. This changing of spins can not only put the atoms into a non-trappable spin state, but also releases energy which heats the atoms up. Either way, atoms that undergo spin exchange collisions are ejected from the trap. In figure 5.2, once the initial fast decay is gone the gas is basically spin polarized into the $F = 2$, $m_F = 2$ state. The lifetime can then be found by fitting to the tail of this decay curve, which gives a $1/e$ background lifetime of 458 s.

If we repeat the same lifetime experiment with just $^6\text{Li}$ in the trap we see in figure 5.3, the $^6\text{Li}$ disappears with a lifetime on the order of 100 s. Since we know the
Figure 5.2  This figure shows a typical lifetime curve for $^7$Li in the $F = 2$, $m_F = 2$ state, in the electro-magnetic trap. The data is taken by holding the atoms in the magnetic trap for a given amount of time, and then probing them by flashing on the MOT beams and detecting the fluorescence on an 8 bit CCD camera. A fit to the tail shows a $1/e$ lifetime of 500 s. The fast initial decay is due to spin exchange collisions caused by non-perfect optical pumping.
Figure 5.3  This shows the spin exchange loss from the magnetic trap for the $^6$Li and the $^6$Li-$^7$Li mixture. The spin exchange occurs since we only optically pump the $^6$Li atoms into the $2S_{3/2} F = 3/2$ manifold. This means we can trap both the $F = 3/2, m_F = 3/2$ and $F = 2, m_F = 1/2$ states. Similarly, poor optical pumping of the $^7$Li allows us to trap the $F = 2, m_F = 2$ and $F = 2, m_F = 1$ states.

background lifetime is 500 s, this decrease must be due to spin exchange between the $F = 3/2, m_F = 3/2$ and the $F = 3/2, m_F = 1/2$ states. On transferring the $^6$Li into the magnetic trap, there is no $m_F$ optical pump so we equally populate two spin states which spin exchange at a rate of $10^{-9}$ cm$^3$/s [7]. This causes the majority of the $^6$Li to be lost within the first 150 s. If we now add the $^7$Li as shown in figure 5.3 we see that there is still a large spin exchange loss initially, however the $^7$Li helps to spin polarize the $^6$Li into the $F = 3/2, m_F = 3/2$ state, recovering 458 s lifetime. This occurs because the desired $^7$Li state, the $F = 2, m_F = 2$, spin exchanges on the unwanted $F = 3/2, m_F = 1/2$ $^6$Li, state spin-polarizing the $^6$Li. Figure 5.3 shows just how the spin exchange decay is modified by the presence of both species in the magnetic trap. This gave us our first indication that we had successfully trapped and spin-polarized a mixed atomic gas of $^7$Li and $^6$Li.
5.3 Dual Quantum Degeneracy

Now that we have been able to load both isotopes into the magnetic trap and spin polarize each into the appropriate state, we cool the mixed gas. The evaporation and accompanying sympathetic cooling works just as explained in chapter 3. The evaporation trajectory worked down to a temperatures of about 1.0 $T_F$ where we found it necessary to slow down the evaporation in order to continue cooling the fermions. As explained in chapter 3, the trajectories speed up near the end of the evaporation to minimize two body losses, however, this increase in evaporation rate adversely affects the sympathetic cooling. This occurs because the last cuts of the evaporation happen faster then the thermalization time for the $^7$Li and the fermion are not efficiently cooled.

Once the atoms are cold, we must implement dual imaging (See chapter 4). The dual imaging allows us to take successive pictures of $^7$Li and then $^6$Li. Figure 5.4 shows three individual cooling cycles each stopped at different final temperatures. The first set show a $^6$Li cloud at 810 nK with $8.7 \times 10^4$ atoms and $T/T_F = 1.0$. The corresponding $^7$Li cloud has $2.4 \times 10^5$ atoms at $T/T_c = 1.5$. The middle set of pictures is at $T = 510$ nK with $1.3 \times 10^5$ $^6$Li atoms at $T/T_F = 0.56$, and $1.7 \times 10^5$ $^7$Li atoms, corresponding to $T/T_C = 1.2$. The lower picture, at $T = 240$ nK, has $1.4 \times 10^5$ $^6$Li atoms at $T/T_F = 0.25$, and $2.2 \times 10^4$ $^7$Li atoms at $T/T_C = 1.0$. Each frame shown corresponds to 1.0 mm in length and 0.18 mm in height. The data were analyzed as discussed in chapter 4. The uncertainties come from the error in the fits and the uncertainty of $\pm 0.5 \Gamma$ in the probe detuning. The error in the fit is found by determining the values of number and temperature that cause a 20% deviation in the $\chi^2$ value. Typical $\chi^2$ values are around 1.1, and the resulting uncertainties are 8% in the temperature and 15% in the number. There is an additional 3% error in determining the 1/e radius of the clouds. This results in a $\pm 9\%$ error in $T/T_F$ and a $\pm 8\%$ error in the quantity $(r/R_F)^2$. This provides solid evidence that we are able to
sympathetically cool a $^6$Li/$^7$Li mixture down to the quantum degenerate regime.

In order to ensure that the observed difference in the size of the Bose and Fermi clouds is due to their different quantum statistical properties and not due to a non-equilibrium effect between the $^7$Li and the $^6$Li or due to heating during the imaging, several precautions were taken. To test that the two gasses where in thermal equilibrium we introduced a parameter called $hol$. The $hol$ parameter, which stands for hold, allows us to vary the amount of time after the evaporation and before the atoms are imaged, essentially holding the $^7$Li and $^6$Li together to allow them to thermalize. $hol$ was varied from 1 ms to 20 s and the relative size of the clouds was monitored. We observed no evidence of the clouds thermalizing, proving that they are already in thermal equilibrium following the evaporation. Further, one can calculate the collision rate

$$R_{7-6} = n \cdot \sigma \cdot V,$$

(5.1)

where $n$ is the density, typically $\sim 10^{12}$ cm$^{-3}$, $\sigma$ is the cross section

$$\sigma = 4 \cdot \pi \cdot a_{7-6}^2$$

(5.2)

and the velocity is related to the temperature by

$$V = \sqrt{\frac{3 \cdot k_B \cdot T}{m}}.$$  

(5.3)

For the combination of $^7$Li in the $F = 2$, $m_F = 2$ and $^6$Li in the $F = 3/2$, $m_F = 3/2$ the scattering length is 40 $a_0$, so at the coldest temperature of 250 nK and the critical density we get a scattering rate 1.9/s or 0.52 s/collision. For all the data at 0.7 $T/T_F$ and higher, $hol$ was 2 s and for the lower temperature data, $hol$ was set to 5 seconds to make certain the clouds were in thermal equilibrium before imaging. For the question of if we are heating the Fermi cloud upon imaging the bosons, we have looked at this two different ways. First, rather than doing the dual imaging, we can just image one cloud per evaporation cycle. Two separate runs to the same
Figure 5.4  This figure shows three independent evaporation cycles stopped at different final temperatures. The top frame shows clouds at $T/T_F = 1$ and $T/T_c = 1.5$. The middle frame shows clouds at $T/T_F = 0.56$ and $T/T_c = 1.2$. The bottom frame shows $T/T_F = 0.25$ and $T/T_c = 1.0$, which is a dual quantum degenerate system. Further the statistical differences in their quantum behavior are manifested in the size discrepancy between the two clouds [17].

temperature. In one run we image just the $^7\text{Li}$ and in the other we image only the $^6\text{Li}$. By this method we observe no difference in Fermi temperature from the case of the dual imaging. The second method used was to measure all leakage light, probing pulse intensities, and durations for imaging the $^7\text{Li}$, and estimate the heating rate. The heating was estimated to be less then 10 pK, or .004% of the coldest temperatures achieved. Based on these observation it is clear that the difference in size of the $^7\text{Li}$ clouds and the $^6\text{Li}$ clouds is a result of their vastly dissimilar quantum nature.

Next, figure 5.5 shows us the cross sections of the top and bottom sets of clouds
in figure 5.4. Figure 5.5 shows us that near $T/T_F = 1$, and $T/T_C > 1$, the $^7$Li and $^6$Li both behave classically and have roughly the same shape at the same temperature. The lower image show a striking difference between the $^7$Li and $^6$Li clouds, due to their distinctly different quantum mechanical nature. As the $^7$Li gas cools and BE statistics take over, the $^7$Li gas becomes narrower and more peaky than it would classically, and the $^6$Li gas does not shrink due the quantum degenerate pressure resulting from the FD statistics. These two opposing quantum effects enhance the difference between the radii of the bosons and fermions highlighting their different quantum mechanical behavior.

The final figure 5.6 show the normalized squared 1/e axial radius of the $^6$Li cloud plotted against $T/T_F$. This is a universal Fermi curve [16] and it shows the normalized squared 1/e radius of the Fermi gas plateaus while the normalized squared 1/e radius of a classical gas approaches zero. The dashed line shows the classical expectation, while the FD expectation is shown by the solid line. The 1/e radius has been
normalized by the Fermi radius $R_F$, where $R_F = (2k_BT_F/m\omega_z^2)^{1/2}$ and $m$ is the mass of $^6$Li. We can clearly see the data diverging from classical statistics and following FD statistics, giving a clear indicator of Fermi degeneracy in $^6$Li.

In the calculation of the Fermi density distributions, a Gaussian approximation was used to convert the observed optical density distribution to the actual density distribution. This same approximation was used in calculating the solid curve in figure 5.6, so they are consistent. We can compare this approximation with the zero temperature distribution from reference [16] and the full calculation at $T/T_F = 0.25$, and we find a 10% error in the curve at $T = 0$, however, in the region of our data, this approximation has less than a 2% error [20]. The approximation can simply be eliminated by doing a full integration of the Fermi density distribution.

Recently, work at the Ecole Normale Supérieure, in Paris, has produced similar results to those presented here [21]. Their setup is quite similar to ours, however, their magnetic trap has trapping frequencies of $\omega_z = 83$ Hz and $\omega_p = 4970$ Hz [21]. Their radial frequency is nearly 10 times larger than ours. This gives a $T_F = 2.8 \mu$K. They have achieved temperatures as low as 0.2 $T_F$ [21]. Their results are consistent with the results presented in this thesis. In particular, it should be noted that comparing their results of the normalized squared radius vs. the normalized temperature, figure 5.6, that the theoretical predictions for the Fermi-Dirac statistics have different zero temperature limits. This occurs for two reasons: First, as explained above, we use a simplifying approximation that has approximately 10% error in the zero temperature limit. Secondly, the limit depends on the trap frequencies. Due to the one dimensionality of the ENS trap, they achieve a zero temperature limit for the normalized squared radius of about 0.13, while the limit for our experiment is 0.48. So, even though the limits differ by over a factor of three, they are consistent due to differences in the two experiments.
Figure 5.6  This figure shows the normalized square radius vs. normalized temperature. The dashed lines show the classical prediction while the solid line shows the prediction for Fermi statistics. The open circles are the data points. The error bars come from the error in measurements described in the text. This clearly shows the deviation from classical statistics into the Fermi degenerate regime.
Chapter 6
Conclusions

6.1 Summary

Here we have described the necessary steps for creating a quantum degenerate mixture of bosons and fermions, specifically, a quantum degenerate mixture of $^7\text{Li}$ and $^6\text{Li}$. Further, we have shown experimental evidence for the first observation of a quantum degenerate Bose/Fermi mixture. The first observation of quantum degenerate $^6\text{Li}$ and the first direct spatial observation of Fermi pressure.

This marks the beginning of a new branch of quantum degenerate studies; the study of Fermi gasses and Fermi/Bose mixtures. We now have the tools to study every aspect of quantum statistics.

6.2 Improvements

The main areas of improvement in the current experiment have to do with the magnetic trap. The current magnetic trap does not switch on in a well mode-matched configuration. Due to a lag in the EMI power supplies, the radial confinement comes on full in less than 200 $\mu$s while the axial field takes nearly 50 ms to energize [7]. As a result, the transfer efficiency from the MOT to the magnetic trap only around 10 %. Further, the mismatched wraps in the quadrupole coils [7] cause a $\sim 1 \mu K$ noise in the bias field. This makes repeatable evaporative cooling to temperatures less than 1 $\mu K$ difficult.

6.3 Future Experiments

The future for this experiment is vast. We are currently implementing a dipole force trap that will allow us to manipulate and study ultra-cold spin mixtures of both $^6\text{Li}$ and $^7\text{Li}$. In particular, we plan to make a large repulsive condensate in the $^7\text{Li}$
F = 1, m_F = 1 ground state. Also, similar to the studies of $^3$He/$^4$He mixtures we plan to study the dynamics and possible phase separation of a quantum degenerate Bose/Fermi mixture.

Further, the ultimate goal of this experiment is observe the BCS phase transition in $^6$Li. To accomplish this task we intend to exploit a Feshbach resonance [22]. This resonance occurs around 830 Gauss [7], and allows the interaction strength between different $^6$Li spin states to be changed. We are currently working on a modified magnetic trap that is capable of producing the large bias field.
References


