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RICE UNIVERSITY

Laserless Slow Atom Source for Loading Atom Traps

by

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A Thesis Submitted
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ABSTRACT

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Permanent magnets are used to selectively remove the fast atoms from an atomic beam and to guide the remaining slow atoms into a trapping region. The permanent magnets establish a quadrupole field which extends along the axis of a bent vacuum nipple. A threshold velocity is set by the radius of curvature of the bent nipple and the strength of the magnets. Only those atoms which are slower than the threshold are transmitted to the trapping region. For a 30 cm radius of curvature and a Maxwellian velocity distribution at the atomic beam source, a flux of $10^9$ atoms/s is expected to be delivered to the trapping region. Experimentally, a flux of only $10^6$ atoms/s is observed. The flux deficit is attributed to an attenuation of slow atoms resulting from collisions within the nozzle of the recirculating oven which is used to produce the atomic beam.
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1 Introduction

The field of atom trapping and laser cooling has seen an explosion of activity over the last couple of decades. Due to the very low temperatures ($\leq 1$ mK) which can be achieved, an atom trap provides a unique laboratory for a variety of interesting experiments. Our group alone has performed notable work in the areas of high precision atomic and molecular spectroscopy [1, 2], and cold-collisional dynamics [3], and most recently has achieved Bose-Einstein condensation (BEC) in a gas of $^7$Li [4]. These experiments were performed in atom traps and represent only a small fraction of the exciting work going on elsewhere. In particular, the achievement of BEC [4]-[6] enables investigations into the so-called quantum degenerate regime where the laws of quantum mechanics dominate, and has precipitated an enormous volume of ideas and experiments, most of which also involve the trapping of atoms. With such a large demand, atom traps have become easier to build, more reliable, and less expensive. The work of this thesis represents another step in the ever improving technology of atom trapping.

At the heart of any atom trap is the method used to load atoms into it. Since it is usually best to trap as many atoms as possible, the load rate of atoms into the trap should be maximized while the loss rate should be minimized. The historically first trap loading technique involves slowing atoms from an atomic beam using radiation pressure from a laser beam directed against the longitudinal motion of the atomic beam [7]. Since only atoms with velocities less than the capture velocity of the trap, $v_c$, are loaded, some longitudinal slowing of the atomic beam is usually necessary. Because the laser beam is directed against the atomic motion, the laser frequency appears higher (bluer) in the reference frame of the moving atoms than it does in the lab frame due to the Doppler shift. Therefore, in order for the laser to be in resonance with a moving atom, the laser is detuned to the red of the atomic resonance in the lab frame by an amount equal to the Doppler shift. However, as the atoms are slowed,
Figure 1.1 Typical scheme for loading a trap from a Zeeman-slowed atomic beam.

the Doppler shift decreases and the detuning of the laser must be adjusted to prolong the slowing process.

The slowing technique first used to load atom traps is called Zeeman-slowng [7] and uses a non-homogeneous magnetic field to shift the atomic resonance frequency as the atoms are slowed. The magnetic field is produced by a tapered solenoid giving a field strength which either increases or decreases with distance from the oven. The solenoid shown in Fig. 1.1 produces a field which increases with distance from the oven and is called a $\sigma^-$ slower [8] since it requires left-circularly polarized light to work properly. Zeeman-slowng works very well and it is the current state of the art method of producing slow atoms for loading traps. Another technique which accounts for the changing Doppler shift of the atoms is called chirp-slowng and involves changing or chirping the laser frequency blue as time progresses [9, 10]. The atoms are slowed in bunches as the chirp is repeated many times. Chirp slowing has been used in our lab in the past [11] but has been abandoned due to the relative complexity compared to Zeeman-slowng and the fact that the atoms are slowed in bunches instead of the CW slowing offered by Zeeman-slowng.

Both the permanent magnet trap and the magneto-optical trap (MOT) [12] used in our lab are loaded from a Zeeman-slowed atomic beam. The loading into our permanent magnet trap saturates in 1 second at about $2 \times 10^8$ atoms [13] while our
MOT saturates in 30 seconds at about $10^8$ atoms. The difference in the two load rates may be attributed to two factors. First, the lithium oven used to produce the atomic beam is run at a higher temperature ($\sim 600^\circ$C) for the permanent magnet trap than for the MOT ($\sim 500^\circ$C), and as App. A shows, the oven flux increases with increasing temperature. Secondly, the permanent magnet trap uses a 22 cm long $\sigma^-$-slower [8] which has been demonstrated to be more efficient than the $\sigma^+$-type slower used for the MOT, which in our implementation is only 10 cm in length.

The necessity for lasers in either Zeeman-slowing or chirp-slowing contributes significantly to the complexity and expense of atom trapping experiments. Additionally, for both methods, the maximum frequency chirp or Zeeman-shift sets the maximum atomic velocity, $v_0$, which can be slowed. Therefore, it becomes technically more difficult to slow a larger portion of the velocity distribution. However, Ref. [14] addresses the subtle issue of whether slowing a larger fraction of the velocity distribution results in a larger slow atom flux. The authors find that for typical experimental conditions, the slow atom flux is roughly independent of $v_0$. For these reasons, it is may be desirable to load the slow atoms already present in the thermal velocity distribution without using a slowing laser.

One technique which eliminates the slowing laser is called vapor loading, where the atoms are loaded into the trap directly from a thermal vapor which exists in the trapping region [15, 16]. Vapor loading has a high load rate since the atoms can enter the trap from any direction. However, the atoms in the vapor which are faster than the trap capture velocity, $v_c$, can collide with the trapped atoms and eject them from the trap. This results in a high trapped atom loss rate which limits the ultimate number of atoms in the trap and limits the length of time which the atoms can be held in the trap. Using vapor loading into a MOT, Ref. [15] reports $\approx 10^6$ sodium atoms and a $e^{-1}$ trap lifetime of $\approx 2$ s, and Ref. [16] reports $1.8 \times 10^7$ cesium atoms with a trap lifetime of $\approx 4$ s. Using Zeeman-slowing, we have loaded $\approx 10^8$ lithium
atoms into our MOT with a trap lifetime of up to 45 s.

An improvement to direct vapor loading has recently been demonstrated by Myatt et al. [17, 18]. This technique involves two MOTs which are separated by a long transfer tube having small conduction. The first MOT collects $\sim 5 \times 10^8$ rubidium atoms directly from a thermal vapor in $\sim 2$ s. Due to the loss mechanisms mentioned above, the number of trapped atoms saturates very quickly. After saturation, the trapping fields are turned off, and a laser pushes the slow atoms which were collected in the MOT into a long transfer tube which leads to another vacuum chamber. A hexapole magnetic field generated by current carrying wires and strips of magnetized rubber (kitchen magnets) situated along the transfer tube confines the slow atoms radially allowing for a $\sim 90\%$ transfer efficiency. The small conduction of the transfer tube allows for the second chamber to be differentially pumped to lower pressure and the transferred atoms can be loaded into another MOT which has a longer lifetime. The loading process can be repeated as many as 30 times resulting in a population in the low-pressure MOT as high as $10^{10}$ atoms with a trap lifetime of 115 s. The $1/e$ fill time for the low-pressure MOT is 95 s. Clearly this technique is highly effective, although it is also much more complicated than direct vapor loading.

Atoms can also be loaded directly from the atomic beam with no slowing laser if the trap is located near the oven nozzle. An improvement can be made by introducing a small atomic beam block positioned directly in front of the trap which keeps the fast atoms in the beam from entering the trap region. Recently, loading of $\approx 10^8$ lithium atoms into a MOT has been achieved in this manner [19]. Unfortunately, due to the proximity of the trapping region to the oven nozzle, the base pressure in the trap chamber for this experiment was typically $2 \times 10^{-9}$ torr. This is a much higher pressure than can be tolerated in many trapping experiments.

In order to take advantage of the simplicity of the direct beam loading technique while maintaining a low base pressure a new loading system is needed. This thesis
reports progress in the development of such a system which uses permanent magnets to select or skim the slow atoms out of the atomic beam and deliver them to the trap. In contrast to a laser-slowed system or the double-MOT system, the skimmer is very simple, robust, and inexpensive and in contrast to the direct vapor or beam loading techniques, a low base pressure is maintained by limiting the conduction between the oven and trap regions. The permanent magnets are maintenance free, require no additional support equipment and can provide atomic accelerations comparable to those provided by typical optical forces. Additionally, since the atoms being skimmed are in the ground state, there is no spontaneous emission, as would be present with the use of lasers, and the quantum mechanical state of the atom is preserved. This can be important if the skimmer is to be used to load a trap, such as a magnet trap, which only captures atoms in a particular quantum mechanical ground state.

Since the skimmer passively selects the slow atoms out of the atomic beam, the flux of atoms the skimmer can deliver to a trap is limited by the number of slow atoms present in the atomic beam. This is in contrast to the velocity compression which laser slowing provides. The skimmer is therefore very sensitive to the distribution of slow atoms emerging from the oven. The calculation in Appendix A shows that the expected flux of atoms with velocities below 100 m/s into the skimmer is $\sim 5 \times 10^8$ atoms/s for a lithium oven temperature of 500°C. The calculation assumes the velocity distribution emerging from the oven is Maxwellian and is for a geometry corresponding to the actual testing of the skimmer. As mentioned previously, the permanent magnet trap used to achieve BEC in our lab only captures atoms with velocities less than $\sim 100$ m/s and the current load rate, using Zeeman slowing, is $\sim 2 \times 10^8$ atoms/s. Therefore, the skimmer should be competitive with laser-slowing if it delivers only 20% of the slow atoms which enter it and if the velocity distribution is Maxwellian.

The remainder of this thesis is organized as follows: Chap. 2 summarizes the skimmer apparatus. Chap. 3 presents a simple model used to determine the motion
of the atoms within the *skimmer* and characterize the performance of the *skimmer*. Chap. 4 describes how the *skimmer* is used to load a magneto-optical trap (MOT) and shows the pertinent experimental results. Chap. 5 demonstrates how the total flux transmitted by the *skimmer* was measured and gives the experimental results. Finally, Chap. 6 summarizes the problems encountered and gives possible remedies and directions for future work.
2 The Skimmer Apparatus

Since the experiment of Stern and Gerlach [20, 21], magnetic fields have been used to manipulate the trajectories of neutral atoms. This classic experiment opened the field of atom optics which has recently produced such novel devices as atomic mirrors, atomic lenses and atomic waveguides [22]. In the field of laser cooling and atom trapping, magnetic fields have been used recently to trap neutral atoms [7] and guide slow atoms from one trap to another [17]. The goal of this work is to use permanent magnets as a low-pass velocity filter, for the purpose of loading atom traps.

As mentioned in Chap 1, the work of Myatt et al [17, 18] involves using magnetic fields to guide the slow atoms from one MOT to another. The hexapole guiding field is produced using a combination of hexapole coils and kitchen magnets arranged along the length of the transfer tube. Since the hexapole coils need about 300 A of current in order to obtain high transfer efficiency, the use of the kitchen magnets alone would be a much more simple solution. Unfortunately, the kitchen magnets allow for significant field fringing and their sole implementation would cause an interference with the MOT magnetic fields. Therefore, the kitchen magnets are restricted to the central region of the transfer tube and the hexapole coils are implemented at the ends and are turned on only during transfer so that their fields do not hamper the trapping ability of the MOTs. This raises the level of complexity of the double MOT apparatus significantly and the use of permanent magnets alone arranged to reduce field fringing would be more satisfying. A system of permanent magnets similar to the ones used for the skimmer system reported in this thesis would possibly allow for the elimination of the hexapole coils and would therefore simplify the double MOT system.

The work of Meschede [23] uses a combination of light forces and permanent magnets to deflect the slow atoms out of an atomic beam. A Zeeman-slowing system
is used to create a large flux of slow atoms and then a transverse laser beam optically deflects the atomic beam. A set of permanent magnets arranged around a bent vacuum nipple produces a quadrupole field which guides only the slow atoms in the beam around the bend. As in the skimmer system reported in this thesis, the work of Meschede uses only permanent magnets to produce the guiding field in contrast to the work of Myatt. The optical deflection allows for the permanent magnets to be inserted into the beam without blocking the slowing laser. Although it is not reported, there is no reason to think that the guided atoms cannot be used to load an atom trap. The major conceptual improvement over the work of Myatt and Meschede which the skimmer provides is the complete lack of laser manipulation of the atomic beam. This translates to simplicity and lack of expense and makes the skimmer concept highly desirable.

The skimmer apparatus consists of two main parts as seen in Fig. 2.1. The oven is responsible for producing the atomic beam. The skimmer is composed of the bent nipple and the permanent magnets and is responsible for removing the fast atoms from the atomic beam while guiding the slow atoms to the trap chamber. The acceptance area of the skimmer is defined by the 6.35 mm inner diameter of the bent nipple. Atoms which emerge from the oven outside the solid angle subtended by this acceptance area are pumped out of the system by a Pfeiffer model TPU064 turbo-molecular vacuum pump. This pump is connected to the source chamber via a 4.5 inch→2.75 inch reducing nipple which conduction limits the effective pumping speed from 60 L/s to 30 L/s. Pressures of \(~5 \times 10^{-9}\) torr are achieved in the source chamber when the oven is run at a temperature of 500°C. A Varian 30 L/s Starcell ion-getter pump, combined with the small conduction (0.1 L/s) of the bent nipple yields a base pressure in the low \(10^{-10}\) torr range for the trap chamber. A low base pressure is important when the atoms guided by the skimmer are to be loaded into a trap as this reduces the loss rate of atoms from the trap.
Figure 2.1  Schematic of the *skimmer* apparatus showing the oven, bent nipple, permanent magnets, source and trap chambers. Inset is a cross-sectional view of one set of quadrupole magnets with the letters indicating the inner tip magnetizations.

2.1 The Oven

Machine drawings for the recirculating oven are shown in Fig. B.1 in Appendix B. The flux of atoms from the oven depends on the oven temperature and the size of the oven aperture through which the atoms must pass. As the calculation in Appendix A shows, for an oven temperature of $500^\circ$C and an aperture inner diameter of 3.56 mm, the oven is expected to flux $5 \times 10^8$ atoms/s for atoms with velocities $\leq 100$ m/s into the *skimmer*. If only 20% of these atoms are delivered to the permanent magnet trap, loading via the *skimmer* will be competitive with the load rate using laser slowing which is $2 \times 10^8$ atoms/s. However, this calculation does not take into account details relating to the recirculating oven which will prove to be important.

The defining feature of the recirculating oven is that atoms which emerge from the
aperture at large angles will strike the nozzle wall and be recycled back into the oven reservoir. This is very useful since it greatly lengthens the time between oven refills.

![Figure 2.2 Schematic of a recirculating oven.](image)

and removes those atoms which do not contribute to the beam. As shown in Fig. 2.2, a thin layer of stainless steel mesh lines the inner diameter of the oven nozzle and decreases the effective aperture diameter from 4.83 mm to 3.56 mm. A temperature gradient is established along the length of the nozzle with the tip (flange end) just above the melting point of lithium (≈ 200°C) and the hottest point at the aperture. Atoms which strike the mesh condense into a liquid and are wicked back towards the aperture where they are again vaporized within the reservoir.

The temperature gradient establishes a density gradient along the length of the nozzle. In order to achieve a suitable atomic flux, the temperature at the oven aperture is maintained relatively high (≈ 500°C). The rate of collisions between atoms in the thermal vapor is given by \( n\sigma(\overline{v})\overline{v} \), where \( n \) is the density, and \( \sigma(\overline{v}) \) is the collisional cross-section for a thermal distribution with average velocity \( \overline{v} \). Since both \( n \) and \( \overline{v} \) increase as the oven temperature is increased, it becomes more probable for an atom to be scattered out of the atomic beam due to collisions within the oven aperture and nozzle. In order for an atom to be sourced from the oven aperture with
high probability, its mean free path must be on the order of the radius of the aperture [24]. The mean free path for an atom is given by its velocity divided by the collision rate, $\lambda(v) = v/(n\sigma(\bar{v})\bar{v})$.

In the summer of 1996, Ashwin Vasan, an REU student from Harvard, calculated $\sigma(\bar{v})$ using the method of partial waves and the details of this calculation are found in Appendix D. Using the results of this calculation, $\lambda$ is calculated straightforwardly. Fig. 2.3 shows $\lambda(v)$ as a function of oven temperature for atoms with $v = 100$ m/s and $v = 190$ m/s corresponding to the capture velocity of the MOT used to test the skimmer (see Chap. 4, and the threshold velocity of the skimmer respectively. The

![Graph showing mean free path as a function of oven temperature](image)

**Figure 2.3** Mean free path, $\lambda$, for a $^6$Li atom as a function of temperature. The solid line corresponds to an atom travelling at 100 m/s while the dashed line corresponds to an atom travelling at 190 m/s.

The temperature range shown is chosen to correspond to the experimental oven temperature range used in this experiment as will be seen in Chaps. 4 and 5. The radius of
the oven aperture is \( \sim 0.18 \) cm and as shown in Fig. 2.3, the oven fails the criteria for effusiveness for atoms less than 100 m/s and 190 m/s at a temperature of \( \sim 430^\circ C \) and \( \sim 450^\circ C \) respectively. It should be reiterated that this criteria is not a sharp threshold for effusiveness and the mean free path can actually be slightly smaller than the aperture radius [24].

2.2 The Skimmer

As shown in Fig. 2.1, the skimmer consists of eight sets of four permanent magnets arranged around a bent vacuum nipple. The four magnets of each set are arranged in a quadrupole configuration and sit in an iron yoke which reduces field fringing. The magnets, made of neodymium iron boron, were purchased from Dexter (part number ND94R4389B). They have an 11 kilo-Gauss (kG) residual induction, measure 0.100 X 0.270 X 0.720 inches, and cost $4.52 each. They have been spray-painted to protect them from oxidation and corrosion. The residual induction is the specified magnetic induction within the permanent magnet, providing a measure of the strength of the magnet. The 90° nipple shown has a bending radius of 10 cm and is one of three which were custom built by Norcal. The other two nipples have bending radii of 20 cm and 30 cm with bend angles of 45° and 30° respectively. The inner diameter of all three bent nipples is 0.25 inches as shown by the machine drawings in Appendix C. It should be noted here that the nipple with the 30 cm bend radius was the only one used in the testing reported in this thesis. The iron yokes were machined in house at Rice.

The field produced inside one of the quadrupole sets of magnets was measured on a cross section using a 3-D Hall probe. The 3-D Hall probe was constructed from three 1-D Hall sensors (model number 1264) obtained from the Seaton Corporation in Carrolton, TX (phone: 214-980-9860). Curtis Bradley machined a precision mount to hold the 1-D sensors at right angles and he built a calibrated electronic driving
unit. A contour plot of the measured magnetic field strength is shown in Fig. 2.4. The magnetic field gradient, \( B_0 \), is approximately the same in both the x and y directions, and the magnetic field has the form \( \vec{B} = B_0 (x\hat{x} - y\hat{y}) \). Along \( y = 0 \), which corresponds to the bending plane of the skimmer nipple, \( B_0 = 1.2 \text{ kG/mm} \) and the maximum field produced at the inner edge of the bent nipple is \( \sim 3.8 \text{ kG} \).

The orientational energy of an atom within an external magnetic field is given by

\[
U = -\vec{\mu}_{\text{atom}} \cdot \vec{B}_{\text{ext}}.
\]

Atoms with magnetic moments antiparallel to the field direction are preferentially driven towards regions of low field and are therefore called low-field-seekers. Since the skimmer has a minimum in magnetic field at the center of a cross-section, atoms which are in low-field seeking states will be guided while those in high-field seeking
states will be driven to the inner wall of the *skimmer* and lost from the beam. Fig. 2.5 shows the energy dependence of the $F = 3/2$ and $F = 1/2$ ground states of $^6$Li on magnetic field strength. These are the relevant states for the testing of the *skimmer*. The nuclear angular momentum $\vec{l}$ decouples from the orbital angular momentum $\vec{J}$.

![Graph showing magnetic sublevels of $F = 3/2$ and $F = 1/2$.](image)

**Figure 2.5** Magnetic sublevels of the $F = 3/2$ and $F = 1/2$. $2S_{1/2}$ ground states of $^6$Li.

when the hyperfine splitting, $\Delta E = 228$ MHz $\leq \mu_B B_{ext}$, where $\mu_B = 1.4$ MHz/G is the Bohr magneton. This occurs at a field of $\sim 150$ G. Since the fields in the *skimmer* are much larger than this, except on axis, the decoupled picture is correct and Fig. 2.5 shows that the low-field-seeking states are those three with $m_J = +1/2$. Therefore, the magnetic moment of the atoms which are guided is $\mu_{atom} = m_J g_e \mu_B \approx \mu_B$, since the gyromagnetic ratio, $g_e \approx 2$ for an electron.
3 Atomic Motion Within Skimmer

In order to determine the motion of atoms within the skimmer a numerical model was constructed as described below. The trajectories of atoms entering the skimmer are integrated and the atoms can be safely guided around the bend or can collide with the inner wall of the bent nipple where they are assumed to stick. Using a Monte-Carlo technique to simulate the initial distribution of atoms at the entrance of the skimmer, the threshold and most probable transmitted velocities of the skimmer are calculated. Using the exit velocities and positions of the atoms and the experimental detection geometry, the detection probability is determined for the atoms which are safely guided. Finally, the effective input area of the skimmer is determined as a function of initial conditions.

3.1 Model Construction

Consider Fig. 3.1 which locally identifies a non-inertial coordinate system, S, at every point along the length of the skimmer having bend radius $R$. $S$ is located at $R\hat{R}$ relative to the origin of the lab frame. For an atom with velocity $v$ to be guided around the bend, the magnetic field must provide the centripetal acceleration, $v^2/R$.

If the Larmor precession of the atom in the magnetic field, $\omega_L$, is much faster than the rate of change of the magnetic field,

$$\omega_L = \mu_{\text{atom}} B / \hbar \gg \frac{1}{B} \left| \frac{dB}{dt} \right| . \tag{3.2}$$

then the magnetic moment of the atom adiabatically follows the magnetic field direction. This is known as the Majorana Criteria [25]. The derivative term on the right side of Eq. 3.2 becomes

$$\frac{dB}{dt} = \left( \vec{\theta} \cdot \vec{\nabla} \right) B \tag{3.3}$$

for an atom with transverse velocity $v$ in coordinate system $S$. The magnetic field strength is assumed to be of the form $B(r) = B_0 \sqrt{r_0^2 + r^2}$, where $r_0 = 1 \, \mu m$ accounts
Figure 3.1 Coordinate systems used to describe the motion of atoms in the *skimmer*. Non-inertial coordinate system $S$ is located at $R\dot{R}$ from the origin of the lab frame, where $R$ is the bend radius of the *skimmer*.

for a $\sim 1$ G bias field at the center of a cross section due to the Earth’s field. As shown in Chap. 2, $\mu_{atom} = \mu_B$ giving for the Majorana criteria

$$\frac{\mu_B B_0}{h} (r_0^2 + r^2)^{3/2} \gg |xv_x + yv_y|,$$

where $v_x$ and $v_y$ are the components of the transverse velocity. If this criteria is violated during the model integration, the atom is assumed to flip its spin and is therefore driven into the *skimmer* wall where it is lost.

From Eq. 2.1 the orientational energy becomes $U = \mu_B B_0 \sqrt{r_0^2 + r^2}$ implying a force of

$$\vec{F} = -\vec{\nabla}U = -\frac{\mu_B B_0}{\sqrt{r_0^2 + r^2}} (x\dot{x} + y\dot{y})$$

in frame $S$. This gives the correct equation of motion if $S$ is at rest. However, to account for the motion of $S$ in the lab frame, we must include the centrifugal
acceleration term, \( (v_0^2 / R) \ddot{z} \), where \( v_0 \) is the initial velocity of the atom along the longitudinal (\( z \)-) axis of the skimmer. Adding this to Eq. 3.5 and separating the motion along \( \dot{x} \) and \( \dot{y} \) gives,

\[
\dot{x} = \frac{F_x}{m} + \frac{v_0^2}{R}
\]

\[
\dot{y} = \frac{F_y}{m}
\]

(3.6) (3.7)

where

\[
F_x = -\mu_B B_0 \frac{x}{\sqrt{r_0^2 + r^2}}
\]

\[
F_y = -\mu_B B_0 \frac{y}{\sqrt{r_0^2 + r^2}}
\]

The trajectory of an atom with given initial conditions is integrated until the atom traverses the entire length of the skimmer, crashes into the wall of the bent nipple, or violates the Majorana criteria. The radial distance which defines the inner wall of the bent nipple is \( r_{max} = 3.175 \) mm.

The Monte-Carlo simulation randomly picks an initial position and transverse velocity from the distributions described below for a given initial longitudinal velocity \( v_z \). The integrator traces the trajectory to determine if the atom is successfully transmitted and this process is typically repeated 5000 times for each value of \( v_z \) in order to obtain good statistics. The distribution of positions at the entrance plane of the skimmer is uniform for radial displacements less than the radius of the oven aperture (1.78 mm) and falls off linearly for larger radii [24]. This effect comes from the tip of the oven nozzle acting as a collimator. For radii larger than the tip radius, the oven aperture area is partially hidden from the line of sight. For an atom which is emitted from a point at the edge of the oven aperture with longitudinal velocity \( v_z \), its initial transverse velocity at the entrance plane of the skimmer is

\[
v_{r, initial} = \frac{r + r_{oven}}{L} \times v_z,
\]

(3.8)
where $r$ is the radial displacement at the skimmer entrance plane. $r_{\text{oven}} = 1.78$ mm is the oven aperture inner radius, and $L \sim 200$ mm is the distance from the oven aperture to the skimmer entrance. Since the maximum radial displacement is just the inner radius of the bent nipple (3.175 mm), then assuming $v_z \sim 200$ m/s. the maximum initial transverse velocity is $\sim 4.5$ m/s. This is small on the scale of this problem, and it doesn't affect the results of the simulation and all atoms are assumed to have no transverse velocity. In the above calculation, 200 m/s was chosen for $v_z$ since this is on the order of the threshold velocity of the skimmer as will be shown later in this chapter.

3.2 Model Results

![Figure 3.2](image.png)

**Figure 3.2** Sample trajectory in the x-y plane for an atom with longitudinal velocity $v_z = 160$ m/s and a skimmer with bend radius 30 cm. (a) Shows the radial displacement as the atom travels down the length of the skimmer. (b) Shows the corresponding motion in velocity space. The start point and end point have been indicated.
Fig. 3.2 shows a sample trajectory in the x-y plane for an atom with $v_z = 160$ m/s as it travels down the length of a skimmer with bend radius 30 cm. Fig. 3.2(a) shows the radial displacement, while Fig. 3.2(b) shows the corresponding motion in velocity space. Clearly, the atom can acquire some transverse velocity as it exits the skimmer, and the longitudinal velocity, $v_z$, must decrease in order to conserve energy. This effect is included in the model by reducing the kinetic energy of the atom at the entrance plane of the skimmer by an amount equal to the magnetic potential energy corresponding to the radial displacement of the entrance point. To be more exact, the initial kinetic energy is given by $KE_{initial} = \frac{1}{2}mv_z^2 - \mu B_0 \sqrt{r_0^2 - r^2}$. Since the atom is initially travelling longitudinally, the initial longitudinal velocity is the quantity which is actually reduced in the model. This effect is unimportant for higher velocities, but if $KE_{initial} \leq 0$, then the atom never enters the skimmer.

Fig. 3.3 shows the transmission and detection probabilities for a skimmer with bend radius 30 cm as a function of the initial longitudinal velocity, $v_z$. The probe laser is modelled to have a diameter of 1.3 cm which matches the experimental conditions. The solid line gives the transmission probability and the dotted line gives the detection probability for those atoms which are successfully guided. The transmission probability is determined from the results of the Monte-Carlo calculation where the number of atoms which are successfully transmitted is tabulated. Fig. 3.3 demonstrates that the threshold velocity for the skimmer with bend radius 30 cm is $\sim 190$ m/s. The small transmission probability at low values of $v_z$ is due to the rejection of atoms at the skimmer input as discussed above. The final trajectories of the atoms as they exit the skimmer determines whether they pass through the detection region. If the atom is within the area subtended by the probe lasers (or MOT lasers) at the center of the probe region, then the atom is considered detected. In the model, this area is taken to be $\pi r_L^2$, where $r_L$ is the radius of the probe laser. This approximation is verified by extending the modelled detection region in either the $\hat{x}$ or $\hat{y}$ direction
Figure 3.3 Transmission and detection probabilities for a skimmer with bend radius 30 cm as a function of the initial longitudinal velocity, $v_z$. The solid line gives the transmission probability and the dotted line gives the detection probability for those atoms which are transmitted and for a probe laser diameter of 1.3 cm.

and in neither case is the result different by more than 10%.

To determine the flux of atoms which is detected using either transverse probing or MOT loading, the transmission and detection probabilities from Fig. 3.3 must first be multiplied together. The result must then be multiplied by the appropriate velocity distribution in order to extract the flux. Fig. 3.4 shows the result of these two operations where the Maxwell-Boltzmann velocity distribution at a temperature of 500°C has been used. Note that the differential flux, $dJ/dv_z$ has already been integrated over the experimental solid angle subtended by the skimmer input, and the flux of atoms with velocities $\leq v_{\text{max}}$ is obtained by integrating $dJ/dv_z$ up to $v_{\text{max}}$. The most probable velocity is shown to be $\sim 170$ m/s.

The modelled detected flux for several values of $v_{\text{max}}$ and oven temperature are
Figure 3.4  Differential flux, $dJ/dv_z$, of atoms expected to pass through the detection region for a skimmer of bend radius 30 cm at an oven temperature of 500°C assuming a Maxwellian velocity distribution. The solid curve denotes $dJ/dv_z$ while the dotted curve is the product of the transmission probability and the detection probability.

shown in Table 3.1. The velocity 100 m/s is relevant since it is the best estimate for the capture velocity of the MOT used to test the skimmer (see Chap. 4) and 190 m/s is relevant since it is the threshold velocity of the skimmer as shown in Fig. 3.3. Also, 510°C corresponds to the peak in the observed total flux (see Chap. 5). 460°C corresponds to the peak in the observed load rate for the MOT (see Chap. 4) and 380°C is the lowest oven temperature used for either type of detection. The reported numbers account for the fact that only half the atoms entering the skimmer are in low-field-seeking states.

It is interesting to determine the distribution of positions at the exit plane of the skimmer as a function of the initial longitudinal velocity, $v_z$. Also, the distribution of
<table>
<thead>
<tr>
<th>Oven Temperature (°C)</th>
<th>$v_{\text{max}}$ (m/s)</th>
<th>Transmitted Flux (atoms/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>190</td>
<td>$1.0 \times 10^9$</td>
</tr>
<tr>
<td>460</td>
<td>100</td>
<td>$1.5 \times 10^7$</td>
</tr>
<tr>
<td>380</td>
<td>190</td>
<td>$1.4 \times 10^7$</td>
</tr>
<tr>
<td>380</td>
<td>100</td>
<td>$9.0 \times 10^5$</td>
</tr>
</tbody>
</table>

**Table 3.1** Modelled detected flux transmitted by the skimmer for velocities $\leq v_{\text{max}}$, assuming a Maxwellian velocity distribution.

atoms at the input plane for those atoms which are not transmitted by the skimmer determines the effective input area of the skimmer for a particular velocity. Fig. 3.5 shows the effective input area and the output distribution side by side for the particular velocities of 60 m/s, 150 m/s, and 180 m/s. The data in the left column are the initial positions of the atoms which are not transmitted by the skimmer while the data in the right column are the final positions of the atoms which are transmitted. Fig. 3.5 demonstrates that the atoms do not enter and exit the skimmer in the same distribution of positions. This is necessary to conserve phase-space density since in general the transverse velocity of the atoms is increased due to the motion within the magnetic potential of the skimmer. The unusual shape of the output distribution is most likely due to chaotic motion within the skimmer which forbids the atoms from entering particular regions. As expected, the effective input area shrinks as the initial velocity is increased. Recall that the x-axis lies in the plane of bending of the skimmer with center of curvature at $x = -R$. Therefore, atoms entering the skimmer at negative values of $x$ receive an initial kick outward due to the centrifugal term in Eq. 3.6. These atoms travel out to larger values of $x$ and have a higher probability of crashing into the wall of the skimmer. Eq. 3.6 also demonstrates that atoms entering at large values of $y$ experience a smaller force in the $x$-direction. As the initial velocity is increased, these atoms will also be pushed into the wall.
Figure 3.5  Effective input area (left) and output distributions (right) for the initial longitudinal velocities of (a) 60 m/s, (b) 150 m/s, and (c) 180 m/s. The shaded regions in the left column correspond to the initial positions of atoms which do not make it through the skimmer and the whitespace therefore corresponds to the effective input area for the velocities given. The shaded regions in the right column correspond to the final positions of atoms which are transmitted by the skimmer. These images are for a skimmer with bend radius 30 cm.
4 Loading a Magneto-Optical Trap

The $^6$Li atoms transmitted by the skimmer were loaded into a magneto-optical trap (MOT) [12] using essentially the same experimental setup shown in Fig. 2.1 except that the nipple with the 30 cm bend radius and 30° bend angle was used. The threshold velocity for this setup is 190 m/s as determined from the model calculations in Chap. 3. The MOT is a precise tool for measuring the slow atom flux transmitted by the skimmer but is only sensitive to atoms which are slower than the capture velocity of the MOT. As will be shown below, the best estimate for the capture velocity of our MOT is $\sim$ 100 m/s. Therefore an alternate method of testing must be employed to determine the total flux of transmitted atoms as described in Chap. 5.

4.1 Method

To load a MOT, the output end of the skimmer is attached to the trap chamber. The MOT consists of three orthogonal pairs of lasers and a pair current carrying coils arranged in an anti-Helmholtz configuration, as shown in Fig. 4.1. When a current of $\sim$ 25 A is run through the coils of our MOT, a quadrupole field is produced with gradients of $\sim$ 53 G/cm in the axial direction and $\sim$ 27 G/cm in the radial direction. The magnetic field Zeeman splits the magnetic sublevels as shown schematically in Fig. 4.2. Quantum mechanical selection rules dictate that only $\Delta m = \pm 1$ transitions are allowed for right or left circularly polarized light respectively. Therefore, suitably chosen polarizations for the lasers give a spatial dependence to the scattering rate for the pairs of lasers and an atom which drifts away from the center of the trap feels a restoring force toward the origin. In order to prevent optical pumping into one of the ground-state hyperfine levels as shown in Fig. 5.3, frequencies corresponding to transitions from both of these ground-state sublevels to the excited state are always simultaneously present. If these two frequencies were not used simultaneously, the atoms would end up in the ground-state sublevel which is "dark" to the laser field and
would no longer interact with the trap laser. A discussion of how these frequencies are generated is given in Chap. 5.

A lens is used to image the fluorescence of the trapped atoms onto a photomultiplier tube (PMT) which is connected to a photon counter. With knowledge of the laser intensity and detuning, the photon scattering rate can be determined from

$$R = \Gamma \frac{I}{1 + 2I + 4\Delta^2(r)} \cdot$$ (4.9)

where $\Gamma$ is the excited state linewidth, $I$ is the laser intensity in units of the saturation intensity and $\Delta(r)$ is the laser detuning from the $2S_{1/2} \rightarrow 2P_{3/2}$ atomic resonance in units of $\Gamma$. The saturation intensity, $I_{sat}$, is the intensity at which the stimulated absorption rate is equal to the spontaneous decay rate. For Li, $\Gamma = 2\pi \times 5.9$ MHz and $I_{sat} = 5.1$ or $7$ mW/cm$^2$ depending on whether the light used is circularly or linearly polarized, respectively. In our MOT, the beams are always circularly polarized and with an intensity of $120$ mW/cm$^2$, $I = 24I_{sat}$. Eq. 4.9 is the steady state solution of the equation describing the evolution of state populations and coherences for a two
level atom. Although Li is not a two level atom, this equation is valid since frequencies corresponding to transitions from both ground state hyperfine levels to the excited state are always present and the system is closed. $\Delta (r)$ is position dependent because the magnetic field gradient Zeeman-shifts the atomic transition as a function of $r$. However, since the maximum shift experienced by the trapped atoms is $\sim 1\Gamma$. and since the zero field detuning is $-9\Gamma$ and $I = 24I_{sat}$ for the MOT lasers, the change in scattering rate due to this effect can be ignored.

If $L$ is the load rate into the trap and $\gamma$ is the loss rate from background gas collisions, the time rate of change of the number of atoms in the trap is given by

$$\dot{N} = L - \gamma N - \beta nN. \quad (4.10)$$

where $\beta$ is the rate of two-body trap loss collisions resulting from collisions between two trapped atoms as defined in Ref. [26]. and $n$ is the atomic density. At equilibrium, $\dot{N} = 0$ and $L = \gamma N - \beta nN$. Suppose the system is at equilibrium with $N_0$ atoms in the trap and at time $t = t_0$ the atomic beam is blocked so that $L = 0$. If the term
involving $\beta$ is small, then the system evolves according to

$$N(t > t_0) = N_0 e^{-\gamma(t-t_0)}.$$  \hspace{1cm} (4.11)

For the experimental conditions achieved in the work of this thesis, the term involving $\beta$ is always observed to be small and the population does follow the form of Eq. 4.11. The equilibrium value of the load rate is determined from the loss rate measured just after the loading is turned off. Therefore, $L_{eq} = N_0 \gamma$. The number of atoms in the trap at a particular time is experimentally given by

$$N = \frac{N_C}{RE}.$$  \hspace{1cm} (4.12)

where $N_C$ is the count rate measured by the photon counter, $R$ is the scattering rate and $E$ is the photon collection efficiency. Therefore the equilibrium value of the load rate is given by

$$L_{eq} = N_0 \gamma = \frac{N_C \gamma}{RE}.$$  \hspace{1cm} (4.13)

### 4.2 Determination of the Capture Velocity

The capture velocity of the MOT will be determined from an approximation of the escape velocity which is defined to be the minimum velocity needed for an atom to escape the trap if it starts at the trap center. The escape velocity depends on the trap laser intensity and detuning, the magnetic field gradient, and the initial trajectory of the atom. As will be shown, the escape velocity is not equivalent to the capture velocity since during capture, the atom does not start at the trap center. Also, the dynamics of an atom moving toward the center of a trap can be quite different than for an atom moving away from the center.

In his thesis [27], Nicholas Ritchie presents a very detailed model which is used to determine the escape velocity for a variety of trap parameters. The escape velocity is an important quantity in studies of trap-loss producing inelastic collisions. The
model integrates the trajectory of the atom until it is determined whether the atom remains trapped or not. If the atom remains trapped, the integration is repeated with a larger initial velocity until the escape velocity for the given initial trajectory is determined. Choosing different initial trajectories and trap parameters allowed Nick to map out the behavior of the escape velocity in a portion of parameter space. Unfortunately, the region of parameter space which was used in the testing of the skimmer does not fall within the map and it is difficult to give an accurate estimate for the escape velocity, which as mentioned above, will be used to approximate the capture velocity. Given this, an attempt at such an estimate follows.

Let us start by giving the values of the parameters which were used while testing the skimmer: the axial and radial magnetic field gradients were 53 G/cm and 27 G/cm, respectively; the trap laser detuning was $\Delta = -9 \Gamma$, where $\Gamma = 2\pi \times 5.9$ MHz is the natural linewidth of $^6$Li; and the total trap laser intensity was $I = 120$ mW/cm$^2$. It should be reiterated that all six lasers are circularly polarized. It should also be noted that in Chap. 4 of [27], the direction which corresponds to the loading axis of the MOT is $(\theta, \phi) = (\pi/2, \pi/4)$. This is important since most of the results presented in that chapter are for the shallowest direction of the MOT which is almost always $(0, 0)$. Fig. 4.3.1 on pg. 87 of [27] gives the escape velocity for the shallowest direction of our $^6$Li MOT as a function of total trap laser intensity for four different trap laser detunings. Although neither the range of intensities ($\leq 22$ mW/cm$^2$) nor the range of detunings shown contain our laser parameters, pg. 86 does give a scaling law for the escape velocity dependence on intensity:

$$v_e = k I^\alpha. \quad (4.14)$$

where $\alpha = 0.124 \rightarrow 0.165$ and $k$ comes from the fit of Eqn. 4.14 to the modelled points in Fig. 4.3.1 of [27]. For $^6$Li and the values of detuning shown, $\alpha$ is found to be 0.124 which gives, for example, $k = 21 \left(\frac{m \text{cm}}{m \text{W}}\right)^\alpha$ for $\Delta = -9 \Gamma$.

At this point, there are two ways to proceed. We can use the four different
detuning values given in Fig. 4.3.1 of [27] and attempt to find a scaling law for the
dependence of $k$ on detuning, which is something Nick does not do. We can then
use this scaling law to find the escape velocity along the shallowest direction for the
correct detuning of $-9\Gamma$. Alternately, we can use Eqn. 4.14 to determine the escape
velocity for one of the four detunings given in Fig. 4.3.1. We can then use Fig. 4.3.2
on pg. 90 which gives the dependence of the escape velocity on trap laser detuning
for the shallowest direction, to scale this result to the correct detuning of $-9\Gamma$. The
results of both methods can then be used to estimate the escape velocity along the
loading axis with the aid of Fig. 4.3.5 on pg. 96 of [27] which gives the dependence
of the escape velocity on the initial trajectory of the atom.

Using the first method, the values of $k$ were plotted for the detunings $-2.3\ \Gamma$, $-2.9\ \Gamma$, $-2.5\ \Gamma$ and $-4.1\ \Gamma$. This was fit to a line of the form

$$k = A + B\Delta. \quad (4.15)$$

giving $A = 7.1 \ \frac{m}{s} \left(\frac{cm}{mW}\right)^{\alpha}$, and $B = -3.4 \ \frac{m}{s} \left(\frac{cm}{mW}\right)^{\alpha}$. For $\Delta = -9\Gamma$, this gives

$k \sim 38 \ \frac{m}{s} \left(\frac{cm}{mW}\right)^{\alpha}$. Using Eqn. 4.14 with $\alpha = 0.124$, the escape velocity for the
shallowest direction, a trap laser detuning of $-9\Gamma$, and a total trap laser intensity of
120 mW/cm$^2$ is found to be $\sim 70$ m/s. This seems reasonable and using Fig. 4.3.5
of [27], the escape velocity for the loading axis ($\pi/2, \pi/4$) can be as much as a factor
of 1.6 larger than for the shallowest direction. This gives $\sim 110$ m/s for the escape
velocity along the loading axis.

To estimate the escape velocity using the second method described above, we must
first use Eqn. 4.14 for one of the four detunings shown in Fig. 4.3.1 for an intensity of
120 mW/cm$^2$. Using $\Delta = -4.1\Gamma$ gives $v_e = 38$ m/s for the shallowest direction. Next
we use Fig. 4.3.2 on pg. 90 of [27] to scale this result to the correct detuning of $-9\Gamma$.
This figure shows that the escape velocity for the shallowest direction and a detuning
of $-9\Gamma$ is a factor of 1.6 larger than for a detuning of $-4.1\Gamma$, giving $v_e = 61$ m/s.
Taking into account the factor of 1.6 for the added depth of the loading axis gives
98 m/s for the escape velocity along the direction of the loading axis. Averaging the result for the two different methods gives 104 m/s for the escape velocity along the loading axis.

To approximate the capture velocity from the escape velocity, it is helpful to think a bit about the difference between dynamics of capture and escape. Fig. 4.2 shows that since the magnetic field is zero at the center of the trap, the Zeeman-shift will also be zero there. If an atom is moving away from the center with high velocity, a large force against its motion is necessary in order for it to be slowed and stay trapped. Therefore, in order to prevent escape, the detuning of the trap laser must compensate for the initial Doppler-shift of the atom since the Zeeman-shift is zero. This means that we expect the escape velocity to scale linearly with laser detuning as shown in Fig. 4.3.2 on pg. 90 of [27]. Now consider capture. During capture, the atom starts far away from the trap center. Therefore, the Zeeman-shift also helps compensate for the Doppler-shift and as the atom enters the trapping region, it feels an opposing force before it ever gets to the trap center. Therefore, the capture velocity should be greater than the escape velocity by an amount for which the Doppler-shift equals the Zeeman-shift. The capture velocity can be found by the addition of a term to the estimate of escape velocity given above which accounts for the Zeeman-shift as an atom enters the trapping region. Using the radial magnetic field gradient of 27 G/cm, the magnetic field at the leading edge of the trapping region is 25 G. This follows from the fact that the trap laser radius is 0.65 cm and the loading axis is along a 45° diagonal to the trapping lasers which lie in the x-y plane in Fig. 4.1. This gives a distance from trap center to leading edge of \(\sqrt{2} \times 0.65 = 0.92\) cm. The corresponding Zeeman-shift is \(1.4 \text{ MHz/G} \times 25 \text{ G} = 35 \text{ MHz} \approx 6\Gamma\). The velocity corresponding to a Doppler-shift of this size is \(6\Gamma \times 3.9 \text{ m/s/}\Gamma \approx 24\) m/s. Therefore, an approximation for the capture velocity using the estimate for the escape velocity given above is 104 m/s + 24 m/s \(\approx 130\) m/s.
Another, more direct estimate for the capture velocity can be obtained with the aid of Fig. 4.2. The capture of an atom from the beam corresponds to the atom moving from right to left in that figure. As the atom enters the trapping region, it must be slowed by the right-circularly-polarized laser beam coming from the left. The atom will scatter photons from that laser at a significant rate when the detuning of the laser from the atomic resonance in the reference frame of the atom is equal to the Rabi flopping frequency:

$$\delta_{\text{atom}} = \Omega = \Gamma \sqrt{\frac{I}{I_{\text{sat}}}}.$$ \hspace{1cm} (4.16)

For an atom which is moving toward the trap center, the effective detuning is $\Delta + \delta_{\text{doppler}} - \delta_{\text{seeman}}$, since the $\Delta m = +1$ transition is shifted farther to the blue on the right side of Fig. 4.2. Plugging this into Eqn. 4.16 and solving for the Doppler-shift gives $\delta_{\text{doppler}} = 5\Gamma + 9\Gamma + 6\Gamma = 20\Gamma$, which corresponds to a velocity of $\sim 80$ m/s. This is an absolute lower limit for the capture velocity. For the remainder of this thesis I will take the approximate average $(100$ m/s$)$ of the capture velocity obtained in the two ways described here to be the best estimate of the capture velocity for the MOT with the understanding that it could be anywhere in the range of $80$ m/s to $130$ m/s.

4.3 Results

Fig. 4.3 shows the photon count rate as a function of time for an oven temperature of $460^\circ$C. The kink in the plot corresponds to the point when the atomic beam is blocked so that $L = 0$. Fitting the signal to a function of the form given in Eq. 4.11 gives $\gamma = 0.1$ Hz for this particular trace with a negligible uncertainty due to the multitude of points used in the fit. With $I = (24 \pm 3)I_{\text{sat}}$ and $\Delta = (-9.0 \pm 0.5)\Gamma$, the scattering rate for the data shown is $(6.4 \pm 0.8) \times 10^{-2}$ $\Gamma$. The quantum efficiency of the PMT is $0.04 \pm 0.01$, and the geometrical photon collection efficiency is $(1.4 \pm 0.2) \times 10^{-3}$. An interference filter is used to filter out wavelengths
Figure 4.3 Decay of the fluorescence signal from the cloud of trapped atoms. The kink in the fluorescence signal corresponds to the point when the atomic beam is blocked. This trace is for an oven temperature of 460°C and corresponds to $\gamma = 0.1$ Hz.

Other than 671 nm corresponding to the resonance wavelength of lithium and this filter is taken to have an efficiency of $0.5 \pm 0.1$. A ND+2 neutral density filter is used so that the PMT is operating under photon-counting conditions and the efficiency was measured to be $(8.6 \pm 1.5) \times 10^{-3}$. The product of all these yields a total photon collection efficiency of $E = (2.5 \pm 1.0) \times 10^{-7}$. Using Eq. 4.13 gives $N_0 = (1.4 \pm 0.5) \times 10^5$ atoms and the load rate $= (1.4 \pm 0.5) \times 10^4$ atoms/s.

As discussed in Chap. 2, there is expected to be an absence of slow atoms emitted from the oven due to collisions within the aperture and nozzle. To investigate this, the load rate is measured for several values of oven temperature as shown in Fig. 4.4. If the oven were effusive for velocities below the capture velocity of the MOT, the load rate would continue to increase as the oven temperature is increased. As shown
in Fig. 2.3, the mean free path for an atom travelling at $v = 100$ m/s at an oven temperature of $460^\circ$C is $\sim 0.07$ cm. This is roughly a factor of 2.5 less than the actual inner radius of the aperture (0.18 cm) as defined by the layer of stainless steel mesh which lines the nozzle. Recall that the condition for effusiveness is that $\lambda$ be on the order of the aperture radius [24]. Therefore, the peak in Fig. 4.4 indicates that at a temperature of $460^\circ$C, the flux of atoms with velocities up to 100 m/s starts to become attenuated due to collisions within the oven aperture.
5 Measurement of the Total Transmitted Flux

It is important to reiterate that the load rate of atoms into the MOT only measures the transmitted flux of atoms with velocities below the $\sim 100$ m/s capture velocity of the trap. This represents only $\sim 8\%$ of the atoms which are guided by the \textit{skimmer} assuming a Maxwell-Boltzmann velocity distribution is emitted from the oven. In order to be sensitive to higher velocities, transverse probing is used.

5.1 Method

The experimental setup is shown in Fig. 5.1 where either the vertical pair of beams or the pair which lie in the plane of the \textit{skimmer} are used. Atoms which pass through the probe region fluoresce and this light is imaged onto the PMT. The

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{schematic.png}
\caption{Schematic of laser setup used for transverse probing. The beam labeled Hor. Probe lies in the plane of bending of the \textit{skimmer} while the beam labeled Vert. Probe is transverse to this plane.}
\end{figure}
probe laser is scanned through the atomic resonance typically with \( I \sim I_{\text{sat}} \). The two laser frequencies, corresponding to transitions from both the hyperfine sublevels in the ground state to the excited state as shown in Fig. 5.3, are always simultaneously present. Without this, the atoms would be optically pumped into one of the ground-state sublevels since an atom in the excited state can decay via spontaneous emission of a photon into either one of the ground-state sublevels. The atoms would therefore become "dark" to the probe laser and optical probing would be ineffective. For lithium, we find it is best to use equal amounts of power in both optical frequencies since the branching ratios from the excited state to either ground state are approximately equal. The "repump" frequency is generated using an acousto-optical modulator (AO). The AO produces optical sidebands shifted in frequency from the carrier at integer multiples of an injected radio frequency. Therefore, by injecting a radio frequency equal to the ground state hyperfine splitting of lithium, the carrier frequency and a first order sideband generate the two needed frequencies. The handy feature of an AO is that the optical sidebands emerge from the AO angularly separated with respect to the carrier and each other and can therefore be used separately. However, for this experiment the two beams are recombined on a beam splitter to form one multifrequency beam.

The flux of atoms passing through the probe laser is given by

\[
J = \frac{N_T \bar{v}}{d} .
\]  

(5.17)

where \( N_T \) is the total number of atoms in the probe region, \( \bar{v} \) is the average velocity of the atoms, and \( d \) is the average length travelled by the atom while being probed. Substituting Eq. 4.12 for \( N_T \) gives

\[
J = \frac{N_C \bar{v}}{REd} .
\]  

(5.18)

where \( N_C \) is the is the count rate registered on the photon counter. \( R \) is the photon scattering rate, and \( E \) is the total photon collection efficiency of the system.
A good estimate for $\bar{v}$ is the most probable velocity of atoms emerging from the \textit{skimmer}. This is calculated in Chap. 3 to be 170 m/s for an initial velocity distribution which is Maxwellian. Although the validity of this assumption is questionable, the average of the actual velocity distribution will undoubtedly be larger than for a Maxwellian distribution so the assumption only underestimates the flux. An estimation for $\bar{d}$ is also needed. If the probe laser is assumed to be no larger than the atomic beam emitted from the \textit{skimmer}, then a conservative estimate for $\bar{d}$ can be obtained from the average of $2y = 2\sqrt{r_L^2 - x^2}$, over $x = -r_L \rightarrow r_L$, where $r_L$ is the radius of the probe laser beam. This yields $\bar{d} = \pi D_L/4$, where $D_L = 2r_L$ is the diameter of the probe laser which has a circular profile. This expression assumes the atomic beam is collimated when passing through the probe laser and therefore overestimates $\bar{d}$ leading to an underestimation of the flux. As discussed in Chap. 3, the probe laser beam diameter, $D_L = 1.3$ cm.

5.2 Results

Fig. 5.2 shows the florescence signal of atoms which emerge from the \textit{skimmer} and pass through the probe region. The laser is scanned through the $2S_{1/2} \rightarrow 2P_{3/2}$ atomic resonance (D2 line) of $^6$Li. Since the optics used for the MOT beams were also used for the transverse probing, one of the lasers which forms the retro-reflected pair is right circularly polarized while the other is left circularly polarized. The total optical power in each of the two sidebands is $P = (2.0 \pm 0.1)$ mW and the gaussian beam waist is $(w = 0.9 \pm 0.1)$ cm. Therefore, the peak intensity is given by $I = 2P/\pi w^2 = (1.7 \pm 0.2)$ mW/cm$^2 = (0.33 \pm 0.04)I_{\text{sat}}$ giving a peak resonant photon scattering rate of $R = (0.20 \pm 0.03)$ $\Gamma$. It should be noted that for the given laser parameters, the intensity at the edge of the laser falls to about 35% of its peak value at the center. This corresponds to a scattering rate which is less than the peak rate by $\sim 50\%$ at the edges of the probe beam. Since the peak rate is the value which is
Figure 5.2  Flourescence signal from atoms in the probing region as the laser is scanned through the $2S_{1/2} \rightarrow 2P_{3/2}$ transition in $^6$Li for a probe laser which lies in the horizontal plane.

used in the analysis below. the reported numbers are systematically off. However, this difference is not expected to be more than 50%. and as will be shown. the deviation of the observed flux from the expected values are much more than this and so the effect is neglected. The number of photons scattered by an atom during probing is given by $t \times R$, where $t = \overline{d}/\overline{u}$ is the time spent by the atom in the probe region. Plugging in for $R$, $\overline{d}$, and $\overline{u}$ gives ~500 photons scattered per atom. The background count rate of ~10$^3$ counts/s due to the scatter of the lasers off the vacuum chamber windows has been subtracted from the signal shown.

The observed splitting of the peak in Fig. 5.2 is repeatable and has several possible explanations. Perhaps the most likely is that it is due to the $^6$Li. $2P_{3/2}$ excited state hyperfine splitting which has a width of 4.6 MHz. However, since the observed
Figure 5.3  Energy level diagram of the $2S_{1/2}$ ground-state and $2P_{3/2}$ excited-state hyperfine sublevels of $^6$Li.

splitting is on the order of $\sim 8$ MHz and the fluorescence features have a width of $\sim 3$ MHz. This explanation is difficult to justify without some additional experimental investigation. Also, as described previously, one of the laser beams which forms the retro-reflected pair is right circularly polarized, while the other is left circularly polarized. Therefore, a small magnetic bias field of $\sim 3$ G in the probe region could Zeeman split the probing transitions by $\sim 8$ MHz which could account for the observed splitting. It is difficult to determine the magnitude of the bias field in the probe region, but fields on the order of 1 G have been measured just outside the vacuum chamber and the Earth's field is of the same order. This explanation is therefore possible, and warrants further investigation. Another possibility is due to the fact that, as noted previously, the two probe laser frequencies were generated using an AO. If the injected radio frequency is offset by $\pm 3$ MHz from 228 MHz, then the optical frequency separation will be offset by the same amount and the two frequencies could come into resonance with the excited state at different times. However, since the
frequency of the signal generator used to drive the AO is stable to better than 1 MHz and was set using a high precision frequency counter. This explanation is unlikely. Additionally, if the two frequencies are not spatially parallel, one of them could pick out a projection of the longitudinal velocity. However, the two frequencies are combined on a beam splitter more than a meter before they pass through a spatial filter, which strictly limits the angular divergence to ~ 0.1°. This corresponds to a frequency shift of ~ 0.4 MHz for a longitudinal velocity of ~ 170 m/s and clearly does not explain the observed splitting. Finally, the D1 line of $^7$Li falls ~ 30 MHz to the red of the D2 line of $^6$Li which is used for probing [28]. Since the recirculating oven is filled with both species, the $^7$Li could be probed simultaneously. However, since the observed splitting in the fluorescence peak is only ~ 8 MHz, this explanation is discredited.

The problem of the observed splitting in the signal is still unresolved. To test its impact on the analysis, the resonant scattering rate for the redmost peak was calculated and the off-resonant rate at a detuning corresponding to the observed splitting was also calculated. These two rates were added together and the sum was inserted into Eq. 5.18 to determine the flux. Since the observed splitting is ~ 1.5 $\Gamma$, the percent change in scattering rate resulting from the inclusion of the splitting is

$$\delta R = \frac{1 + 2I}{1 + 2I + 4(1.5)^2} \sim 15\%.$$ (5.19)

for $I \sim I_{sat}/3$, and the effect is neglected.

The flux of atoms transmitted by the skimmer can now be determined using Eq. 5.18 by inserting the resonant scattering rate for the redmost peak. With an ND+0.5 neutral density filter replacing the ND+2 filter used with the MOT, the collection efficiency is $E = (9.1 \pm 3.6) \times 10^{-6}$. Fig. 5.4 shows the dependence of flux of atoms computed in this way on the oven temperature for a vertical transverse probe and represents all the data taken for a vertical probe. As in the case of loading the MOT, the flux of atoms is seen to decrease beyond a certain temperature. Compared
Figure 5.4 Measured flux of atoms as a function of oven temperature. The uncertainty for each point is $\pm 45\%$. The probe laser lies along a vertical axis, has intensity $I = \frac{1}{3} I_{sat}$ and has diameter 1.3 cm.

to Fig. 4.4 the peak in Fig. 5.4 is offset from $460^\circ C$ to $510^\circ C$. Fig. 2.3 shows that the mean free path of an atom with velocity 190 m/s for an oven temperature of $510^\circ C$ is $\sim 0.04$ cm. Once again, this is the range in temperature where the oven is expected to become non-effusive for these velocities and Fig. 5.4 supports this.

Table 5.2 summarizes the data taken using a horizontal transverse probe. To compare with the model predictions, the results obtained using a probe diameter of 1.3 cm must be used. As expected, the observed flux is independent of the laser intensity. The roughly factor of three larger signal obtained for a horizontal probe rather than a vertical one is most likely due to detection geometry. For a vertical probe (data shown in Fig. 5.4), the PMT is positioned along an axis perpendicular to the probe beams while for a horizontal probe (data shown in Table 5.2), it is positioned along an axis at $45^\circ$ to the probe beams. Therefore, the projection of the detection volume onto the PMT is $2\sqrt{3}$ times larger when a horizontal probe is used.
<table>
<thead>
<tr>
<th>Laser Intensity ($I_{\text{sat}}$)</th>
<th>Laser Diameter (cm)</th>
<th>Observed Flux ($10^6$ atoms/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>1.1</td>
<td>$(1.9 \pm 0.9)$</td>
</tr>
<tr>
<td>0.26</td>
<td>1.1</td>
<td>$(1.9 \pm 0.9)$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.75</td>
<td>$(1.5 \pm 0.7)$</td>
</tr>
<tr>
<td>0.5</td>
<td>1.1</td>
<td>$(2.1 \pm 0.9)$</td>
</tr>
<tr>
<td>1.1</td>
<td>1.3</td>
<td>$(2.3 \pm 1.0)$</td>
</tr>
</tbody>
</table>

**Table 5.2** Summary of data taken for a horizontal transverse probe at an oven temperature of 510°C.

The data of Fig. 5.4 can be normalized to the data of Table 5.2 by multiplying by this factor of $2\sqrt{2}$. This is done in Chap. 6 in order to compare the observed flux values with the expected flux values at an oven temperature of 380°C since only data taken with a vertical probe was taken for this temperature.
6 Conclusions

A direct comparison can now be made between the expected flux as calculated in Chap. 3 and presented in Table 3.1 and the experimental observations presented in the previous two chapters. Table 6.3 is such a comparison where the column labeled "Expected Flux" is a simple reproduction of Table 3.1. The column labeled

<table>
<thead>
<tr>
<th>Oven T (°C)</th>
<th>$v_{max}$ (m/s)</th>
<th>Expected Flux (atoms/s)</th>
<th>Observed Flux (atoms/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>190</td>
<td>$1.0 \times 10^3$</td>
<td>$(2.3 \pm 1.0) \times 10^8$</td>
</tr>
<tr>
<td>460</td>
<td>100</td>
<td>$1.5 \times 10^7$</td>
<td>$(1.4 \pm 0.5) \times 10^4$</td>
</tr>
<tr>
<td>380</td>
<td>190</td>
<td>$1.4 \times 10^7$</td>
<td>$(2.8 \pm 0.5) \times 10^5$</td>
</tr>
<tr>
<td>380</td>
<td>100</td>
<td>$9.0 \times 10^5$</td>
<td>$(3 \pm 1.2) \times 10^3$</td>
</tr>
</tbody>
</table>

Table 6.3 Comparison of the expected and observed flux transmitted by the skimmer. The expected flux is integrated for velocities up to $v_{max}$.

"Observed Flux" is experimental data obtained from loading a MOT or transverse probing for: $v_{max} = 100 \text{ m/s}$ and $190 \text{ m/s.}$ respectively. Obviously, the predicted and observed values do not agree. We believe that the skimmer is well characterized by our model and therefore, we believe that the recirculating oven accounts for the bulk of missing atoms. There is simply a deficit of slow atoms emerging from the oven which fundamentally limits the number of atoms which the skimmer can transmit. The fact that the expected and observed values agree better for lower oven temperatures supports this idea since the oven is expected to become more effusive as the temperature is decreased.

Let us now investigate the nature of the missing flux of atoms quantitatively. The probability for an atom of velocity $v$ to traverse a length $dr$ in a gas without undergoing a collision is $e^{-dr/\lambda}$ [24], where $\lambda = v/(n\sigma\overline{v})$ is the mean free path. $n$ is the density, $\sigma$ is the collisional cross section, and $\overline{v}$ is the mean velocity in the gas.
Therefore, the probability for an atom to be transmitted through a gas of length $L$ is

$$P_G = e^{-\int_0^L \frac{dr}{\lambda}}.$$  \hfill (6.20)

Consider the density at a distance $r$ from an oven aperture of radius $r_0$. If the density at the aperture is $n_0$, then $n(r) = n_0(r_0/r)^2$. So the integral in Eqn. 6.20 becomes

$$\int_0^L \frac{dr}{\lambda} = \frac{r_0^2}{\lambda_0} \int_{r_0}^{L} \frac{dr}{r^2} = \frac{r_0}{\lambda_0}.$$  \hfill (6.21)

for $L \gg r_0$, where $\lambda_0 = \lambda(r = r_0)$. For the recirculating oven, $r_0 = 0.18$ cm and $L \approx 19$ cm is the distance from the aperture to the skimmer. Therefore the condition holds and Eqn. 6.20 is valid.

This can be included in the model which calculates the expected flux as presented in Chap. 3. The Maxwell-Boltzmann distribution as given in App. A is multiplied by $P_G$ for each velocity at a particular oven temperature. This modified Maxwell-Boltzmann is then multiplied by the calculated transmission and detection probabilities. The result is integrated up to the velocity of interest to obtain the expected flux at the given oven temperature. This procedure is exactly the same as that performed in Chap. 3 except that now we have modified the Maxwell-Boltzmann velocity distribution to account for the probability that an atom ever reaches the skimmer input in the first place. Fig. 6.1 shows the expected flux as a function of oven temperature for the measured aperture radius of 1.778 mm and the MOT load rate data from Chap. 4. The disagreement between the modeled flux and the data indicates that the recirculating oven is not behaving at all like a simple aperture. This is not surprising since, as described in Chap. 2, the atoms must pass through the heated nozzle before they enter the vacuum chamber. The temperatures in the nozzle allow for atoms to be sourced from the nozzle walls imposing a density gradient along the its length. Although the dynamics within the nozzle are complicated and difficult to model, a close examination of Fig. 6.1 yields some insight into what is happening.
Figure 6.1 Expected flux as a function of oven temperature assuming a modified Maxwell-Boltzmann velocity distribution and an aperture radius of 1.778 mm. The experimental MOT load rate data is also shown for reference. Note that the data uses scale on the left, while the model predictions use the scale on the right.

At low temperatures, the predicted flux is larger than the observed load rate. This indicates that the densities in the recirculating oven nozzle are larger than for a simple aperture resulting in a suppression of the slow atom flux. This is shown in Fig. 6.2 which compares the density in an oven nozzle to that in free space as a function of distance from the aperture. The temperature gradient in the nozzle is approximated by $T_0 e^{-r/2L}$ where $T_0 = 500^\circ C$ for the plot shown and $r$ is the distance from the oven aperture. For the trace corresponding to free space, the density follows the form $n(r) = n_0 (r_0/r)^2$ where $n_0$ is the density at $r = 0$ and $r_0$ is the aperture radius. At higher temperatures, the predicted flux in Fig. 6.1 underestimates the observed load rate. This is only possible if the slow atoms are sourced from a point somewhere down the nozzle instead of from the aperture. This is supported by the
Figure 6.2 Comparison of the density in free space and the density in an oven nozzle as a function of distance from the aperture. The temperature at the aperture is 500°C and the aperture radius, \( r_0 \), is 1.778 mm.

fact that if the nozzle density distribution is used in Eqn. 6.21 instead of the free space density, the probability for an atom of velocity 100 m/s to be sourced from the recirculating oven is 0. If the integral is made to start from a point farther down the nozzle instead of at the aperture, the probability increases to something reasonable.

It would be useful to characterize the slow atom flux which the recirculating oven provides, but it is very difficult to make such a measurement and previous attempts have failed. As mentioned, it is also very difficult to model the recirculating oven and it may be easier to simply use an oven which should be more effusive for slow atoms. The oven design of Fig. B.2 in Appendix B has been manufactured and is waiting to be tested. Compared to the recirculating oven, the nozzle has been shortened from 3" to just 0.25" and an expansive tube has been added to the flange side so that the transition from the region of high density near the aperture to a low density region is as fast as possible. The aperture diameter has also been enlarged slightly from 4.83
mm to 5.33 mm so that the oven can be run at lower temperatures. The expansive tube can be lined with a gettering material which will help to remove the atoms which emerge from the aperture at large angles. Although this oven does not recycle the large angle flux, it should be more appropriate for the skimmer application.

It may be possible to compensate for the deficit of slow atoms by simply moving the skimmer input closer to the oven aperture. This would greatly increase the number of atoms entering the skimmer leading to an increase in slow atom flux. The idea of putting at least some of the magnets inside the vacuum chamber needs to be explored and the new oven design would be ideal for this since there is plenty of room for magnets within the expansive tube. Another idea is to attach the skimmer input directly to the oven output with no vacuum chamber in between. The oven temperature could be run low to minimize the vapor pressure. Theoretically, this should work since only slow atoms should be transmitted by the skimmer to the trap chamber. However, with no pumping on the source chamber, the pressure at the skimmer input could be sufficiently high to prevent transmission of the slow atoms into the skimmer and this is a concern. Finally, it may be possible to optically “funnel” more atoms into the skimmer by constructing a two-dimensional MOT just in front of the skimmer input [29]. However, as this design would be significantly more complex than the alternatives mentioned above, it is viewed as a last resort.

The highest priority for future work is to test the new oven and investigate the ideas presented above. Also, the origin of the splitting in the transverse probing fluorescence peak described in Chap. 5 needs to resolved. As mentioned, the resolution of this issue is not expected to greatly affect the results of the analysis but it should be investigated if similar testing methods for the skimmer are employed in the future. However, as alternate methods of testing, such as loading a permanent magnet trap, might be employed, this issue may never be settled. Since the atoms are diverging as they are emitted from the skimmer, one obvious improvement to the system is to
move the *skimmer* output much closer to the trapping region in order to capture or detect all the atoms which are emitted.

A serious investigation into the nature of the unusual distribution of atoms at the *skimmer* exit plane as shown in Fig. 3.5 might be useful. One idea is to use this information to characterize the *skimmer* in a way which is similar to the characterization of optical components. The output distributions shown in the right column of Fig. 3.5 can be considered the images of the input distribution given by the whitespace shown in the left column. This is in direct analogy to the formation of a light image by conventional optics. A point transfer function of sorts which maps every point at the input plane to a corresponding point at the output plane could be generated for different initial conditions.

One useful application of such information would be to characterize the slow atom flux from an oven. A thin sheet of laser light could be positioned directly after, and parallel to, the output plane of the *skimmer*. The fluorescence, as atoms pass through the laser beam, could be imaged onto a CCD camera in order to view the output distribution directly. Since the point transfer function of the *skimmer* depends on the initial longitudinal velocity of the atoms, the image would represent the convolution of the point transfer function with the initial velocity distribution. The numerically generated point transfer functions could be inserted and the velocity distribution could be backed out. Although this technique would be difficult to implement, it could be a useful diagnostic tool for atomic beams.

Perhaps the most exciting potential application of the *skimmer* is to simultaneously load $^6$Li and $^7$Li into a trap for the purpose of performing quantum degenerate experiments with a system of fermions. Since the *skimmer* should perform equally well with the bosonic $^7$Li and the fermionic $^6$Li it should be ideally suited for such an application. For technical reasons, a bosonic species must be simultaneously present in order to achieve the temperatures neccessary for quantum degeneracy in a fermionic
system. The cooling mechanism used to produce quantum degeneracy is called forced evaporative cooling [30], and it relies on the ability of the trapped sample to thermalize through collisions. Since the exchange of two identical fermions is forbidden by quantum mechanics, s-wave collisions between identical fermions are also forbidden. At the ultralow temperatures necessary for quantum degeneracy, only s-wave collisions are energetically possible and therefore no collisions between identical fermions in an ultracold atom trap are possible. If a bosonic species is also present, then the fermions can thermalize through collisions with the bosons as they are evaporatively cooled and quantum degeneracy can be achieved [31]-[18].

In order for the skimmer to be useful for loading both $^7$Li and $^6$Li simultaneously, the load rate of $^7$Li must be $\geq 10^8$ atoms/s for velocities less than 100 m/s. This load rate is the minimum necessary for efficient evaporative cooling of $^7$Li in the permanent magnet trap used to produce BEC in our lab resulting from the fact that many atoms are lost in the evaporative cooling cycle [4]. The permanent magnet trap has a capture velocity of $\sim 100$ m/s and is currently loaded via Zeeman-slowing [13]. If the skimmer can be improved to perform at this level, then it can be used to load both species simultaneously. However, even if the skimmer never performs up to this standard, it can be used at its current performance level to load $^6$Li since the $^6$Li atoms are not expected to be lost due to the evaporative cooling. Even such an application would greatly reduce the complexity of this experiment since it would eliminate the need for at least two laser beams of different frequencies.
A Flux of Atoms Through an Aperture

Figure A.1 Coordinate system used to calculate flux of slow atoms passing through an oven aperture of area $A$.

In general the flux $J$ is given by

$$J = nA\langle v_z \rangle. \quad (A.22)$$

where $n$ is the atomic density and $\langle v_z \rangle = \langle v \cos \theta \rangle$ is the average velocity perpendicular to the aperture. The density for a vapor at temperature $T$ in kelvin is

$$n = \frac{P}{k_B T} = 10^{33} \times \frac{e^{-18674/T}}{T}. \quad (A.23)$$

where the vapor pressure is given by $P = 1.3 \times 10^{19} e^{-18674/T}$ Pa, and $k_B$ is the Boltzmann constant. To find $\langle v_z \rangle$, assume a Maxwell-Boltzmann velocity distribution within the oven.

$$f_0(p) = \frac{1}{(2\pi m k_B T)^{3/2}} e^{-\frac{p^2}{2mk_BT}} = \frac{1}{(2\pi m k_B T)^{3/2}} e^{-\frac{m p^2}{2k_BT}}. \quad (A.24)$$
where $m$ is the atomic mass, and $\bar{p} = mv$ is the momentum. Then $\langle v_z \rangle$ is given by

$$
\langle v_z \rangle = \int v_z f_0 d^3 \bar{p} = \left( \frac{m}{2\pi k_B T} \right)^{3/2} \int e^{-\frac{m v^2}{2 k_B T}} v^3 \cos \theta \sin \theta d\theta d\phi dv .
$$

(A.25)

where the relationship for the three-dimensional differential. $d^3 \bar{p} = p^2 \sin \theta d\theta d\phi dv = m^3 v^2 \sin \theta d\theta d\phi dv$. has been used.

We are only interested in atoms which can be guided by the skimmer. Therefore, the exponential in Eq. A.25 can be brought out of the integral since the threshold velocity for the skimmer is 200 m/s, giving

$$
e^{-\frac{m v^2}{2 k_B T}} = e^{-4.5 \times 10^{-3}} = 0.982 \approx 1 .
$$

(A.26)

for an oven temperature of 500° C. The integral over the velocity becomes

$$
\int_0^{v_{\text{max}}} v^3 dv = \frac{v_{\text{max}}^4}{4} .
$$

(A.27)

Since the distance from the oven aperture to the skimmer input is 7.4 inches and the inner radius of the skimmer tube is 0.125 inches. $\theta = 0 \rightarrow 0.017$ and the integral over $\theta$ and $\phi$ becomes

$$
\int \cos \theta \sin \theta d\theta d\phi = 2\pi \int_0^{0.017} \cos \theta \sin \theta d\theta = 9 \times 10^{-4} .
$$

(A.28)

Finally, the prefactor of Eq. A.25 is for $^6\text{Li}$

$$
\left( \frac{m}{2\pi k_B T} \right)^{3/2} = 1.2 \times 10^{-6} \times T^{-3/2} \left( \frac{s}{m} \right)^3 .
$$

(A.29)

Therefore, the flux of atoms with $v < v_{\text{max}}$ into a solid angle subtended by the skimmer input is given by

$$
J(\text{atoms/s}) = n A(v_z) = 2.7 \times 10^{18} \times \frac{e^{-18674/T}}{T^{5/2}} \times v_{\text{max}}^4 ,
$$

(A.30)

with $v_{\text{max}}$ in m/s. This is only valid for the geometry of the skimmer, and an aperture area defined by the inner radius of the mesh which lines the oven nozzle. $A = 1.0 \times 10^{-5} \text{ m}^2$. 

B Oven Machine Drawings

Figure B.1 shows a machine drawing of a recirculating similar to the one used in this experiment. The actual oven used was identical except that it was mounted on a 2.75” conflat flange instead of a 4.5” one. Figure B.2 shows a machine drawing of the new oven designed to be more effusive for slow atoms. The nozzle is shortened from 3” to 1/4” so that the density of atoms should fall off more rapidly in the new design. Also, the expansive tube at the end of the nozzle can be lined with gettering material to provide pumping of the atoms which emerge at large angles.
Figure B.1 Recirculating oven used in this experiment.
Figure B.2  New oven designed to be more effusive for slow atoms.
C Skimmer Machine Drawings

Figure C.1 Bent *skimmer* nipple with 10 cm bend radius.
Figure C.2 Bent skimmer nipple with 20 cm bend radius.

Rotatable (tapped) 1.33"
Conflat Flange (one)

7.874" +/- 0.020"

45°

Rotatable (not tapped)
1.33" Conflat Flange (one)

7.874" +/- 0.020"
[20.00 cm +/- 0.05 cm]

Tube: ID 5/16" ID 0.240-0.252"
Figure C.3  Bent skimmer nipple with 30 cm bend radius.
D Calculation of Collisional Cross-Section

This appendix summarizes the work done by Ashwin Vasan, an REU student from Harvard, who worked in our lab during the summer of 1996 and gives some comments on how his work was used in this thesis. In particular, Ashwin performed a calculation to determine the cross-section of a binary collision between two $^7$Li atoms and this thesis uses the results to determine the mean free path of a $^6$Li atom. Although the calculation was performed for $^7$Li, at the high energies considered here, the cross-section for $^6$Li should be almost identical.

![Graph showing interatomic potential for two ground-state $^7$Li atoms.]

**Figure D.1** Interatomic potential for two ground-state $^7$Li atoms.

To determine the cross-section Ashwin used the method of partial waves whereby the incident wavefunction is decomposed into spherical partial waves. The dynamics of a binary collision between ground-state lithium atoms is governed by one of two interacting potentials, the triplet and the singlet, depending on whether their angular
momentum vectors sum to 1 or 0 respectively. These potentials are shown in Fig. D.1 for $^7\text{Li}$. The collisional phase shift, $\delta_l$, for each of the $l$ partial waves is calculated by solving the Schrödinger equation in radial form for each of the potentials. This part of the computer code was supplied by Cass Sackett. Next, the phase shifts are inserted into the partial wave series:

$$f(\theta) = \frac{1}{2ik} \sum_{l=0}^{\infty} (2l + 1)(e^{2i\delta_l} - 1)P_l(\cos \theta).$$  \hspace{1cm} (D.31)

where $i = \sqrt{-1}$, $k$ is the magnitude of the wavevector, $\theta$ is the angle between the initial trajectory and final trajectory, and the $P_l$'s are the Legendre polynomials. $f(\theta)$ is termed the scattering amplitude and is related to the total cross section through.
the optical theorem:

\[ \sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im}[f(\theta = 0)]. \]  

(D.32)

Obviously, a numerical calculation cannot complete the sum of Eq. D.31, and it is necessary to determine how many partial waves are needed for convergence. Fig. D.2(a) demonstrates explicitly how the cross section converges as more partial waves are added. As Fig. D.2(b) shows, the number of partial waves needed is linear with collision energy. The results of Ashwin's calculation for the collisional cross section are shown in Fig. D.3 for both the triplet and singlet potentials as a function of the collision energy. As the collision energy approaches zero, the cross section approaches \(4\pi a^2\), where \(a\) is the s-wave scattering length which has been determined spectroscopically [1]. The cross sections shown are used to compute the mean free

\[ \text{Cross Section (}10^{13} \text{ cm}^2) \]

\[ \text{Collision Energy (K)} \]

*Figure D.3* Singlet and triplet collisional cross sections for \(^7\text{Li}\) as a function of the collision energy.
path, $\lambda$, for $^6$Li atoms as discussed in Chap. 2. In order to account for the fact that a binary collision can be along either the triplet or singlet potential, an average of the cross sections must be computed:

$$\sigma_{\text{ave}} = \frac{3\sigma_{\text{trip}} + \sigma_{\text{sing}}}{4}. \quad (D.33)$$

This is the appropriate average since there are three possible projections of the total angular momentum which lead to interaction along the triplet potential, while there is only one such projection for the singlet potential.
References


