ABSTRACT

AN IMPROVED LASER COOLING AND ATOM TRAPPING SETUP
FOR OPTICAL LATTICE AND RATCHET EXPERIMENTS

by Shan Zhong

In this thesis, we will present in detail how we setup the laser, vacuum, and imaging systems in the new lab. We obtain significant improvements over the previous experimental setup. We discuss future experiments on optical lattices, and ratchets.
AN IMPROVED LASER COOLING AND ATOM TRAPPING SETUP
FOR OPTICAL LATTICE AND RATCHET EXPERIMENTS

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To my loving family
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Chapter 1

Introduction

In this chapter we will layout the background of laser cooling and trapping, optical lattices and ratchets in Section 1.1. In Section 1.2 we discuss the general organization of this thesis.

1.1 Motivation and Background

Physicists have been interested in the interaction between light and matter for centuries, starting from Maxwells prediction that electromagnetic radiation could radiation pressure. The idea that the radiation pressure of a laser beam on free atoms could be velocity dependent and therefore be used for slowing and cooling atomic sample was first proposed by Wineland and Dehmelt, Hansch and Schawlow, and Wineland and Itano independently in 1970s. Later in 1985, Steven Chu’s group demonstrated a three dimension atomic confinement in an optical dipole trap, named “optical molasses”, and successfully trap the sodium atoms for 0.1s and cooled them to 240 $\mu K$. And one year later, in 1986, David Pritchard built the first magneto-optical-trap (MOT) which is the workhorse for cold atom experiment today.

The MOT and molasses are based in novel sub-Doppler cooling mechanism which caused by the polarization gradient of the light resulting from the interplay between spatial modulation of the AC stark shift in the atomic ground state, and optical pumping. Because the atoms are forever climbing hill in a widely used laser configuration (the so-called lin$\perp$lin case). Sub-Doppler cooling is called Sisyphus cooling in reference to the Greek myth
of Sisyphus who was condemned to forever roll a stone up an impossible hill.

Optical lattices and ratchets are currently popular topics in AMO physics. Optical lattice was first observed in 1992\textsuperscript{7,8}. By creating an optical lattice, one can model and explore condensed matter problems in these arrays of microscopic traps. It has been noted that the transport behavior of cold atoms in dissipative optical lattices cannot be described by Boltzmann-Gibbs statistical mechanics\textsuperscript{9}. For example, in the quantum degenerate limit, loading a Bose-Einstein condensate (BEC) into an optical lattice opens doors for a variety of experiments in condensed-matter simulations, atomic clocks, and quantum computers\textsuperscript{10}. Interesting experiment remain even in the non-degenerate regime. It has been argued that the optical lattice is an ideal system for observing anomalous diffusion and Lévy statistics\textsuperscript{11}.

Optical ratchets can be made by applying a time-dependent force with zero average to drive a system away from equilibrium. The experimental investigation of optical ratchets has been carried out using cold atoms in optical lattice\textsuperscript{12}. Optical ratchets have been attracting attention in different communities for applications to a variety of topics ranging from particle separation to molecular motors and nanoengineering in biophysics\textsuperscript{13}.

Our research focuses on building an optical lattice and studying the transport behavior of cold atoms. Since we just moved from one building to another last summer, everything had to be disassembled and then reassembled in the new lab. In our new lab, we have so far set up the laser systems and the MOT, and was in the middle of recreating the optical lattice which we had in the old building. We have implemented several minor improvements that were long overdue but could have only be incorporated during a complete re-building of the experiment from scratch. These improvements are significant because they ease the life of experimenter. For example, floating optics tables have now been implemented with laser beams going from one table to the other through optical fibers, allowing alignment to be performed around the cold atom sample on the table with no fear of the accompanying mechanical motions affecting the stability of the frequency-locked laser systems which sit on the other table.
1.2 Thesis Organization

This thesis is organized as follows:

In chapter 2, we describe the experimental setup for our MOT, lattice beam imaging beam, and also describe the new vacuum system setup. We provide details of the design and implementation of a low-cost high-power laser system and low-cost fast imaging system.

In chapter 3, we present data on the temperature, number and number density of our cold atom sample. We also made a preliminary measurements of the spatial diffusion rate, and tracked the Center of Mass of expanding molasses.

In chapter 4, we discuss some future experiments on the optical lattices, optical ratchets, and the measurement of polarization-selective intensity correlations.
Chapter 2

Experimental Setup

In this chapter, we will talk about how the laser, vacuum and imaging system setup for trapping and imaging cold atoms.

2.1 Creating Magneto-Optical Trap

2.1.1 Laser System

Tunable laser diodes are widely used in laser cooling and trapping experiments. Compared to dye or Ti-sapphire lasers, tunable laser diodes are much less expensive yet reliable sources of narrow band width light\textsuperscript{14}. Additionally, the technique of optical feedback laser control can be used to improve the frequency tuning characteristics of the light from an off-the-shelf laser diode.

In our lab, we use an external cavity diode laser (ECDL) system which is a simple and inexpensive homemade laser system based on the design in Ref.[14]. This laser diode system uses optical feedback from a diffraction grating and produces over 20mW of narrow bandwidth light which can be easily tuned over atomic resonance lines.

There are four main components of our ECDL: a commercial diode laser bought from Thorlabs (model number L785P090), a collimating lens, a beam splitter, and a diffraction grating. These components are mounted on a base-plate as shown in Fig. 2.1. The non-polarized beam splitter in between the
Figure 2.1: a) The ECDL system in our lab. We inserted a non-polarizing beam splitter so that we can have two beams coming out of the box in two different directions. b) The design in Ref[14], reproduced from http://photonicssociety.org/newsletters/jun99/diode.htm

diffraction grating and laser diode splits the laser beam into a strong beam which is used for laser cooling and trapping, and a weaker beam, which is used for saturated absorption spectroscopy (SAS). The diffraction grating is mounted in the Littrow configuration so that the -1 order of the diffraction beam can be made to overlap the incident beam and reflected back into the laser diode. As such, the light bounces back and forth in the cavity which is made by the grating and diode. By tuning the horizontal and vertical knob on the kinematic mount one can change the angle of the diffraction grating to vary the output frequency of the laser diode (see Fig.2.1).

The laser system also requires a stable low-noise current controller to run the laser, and a control circuit to stabilize the diode and baseplate temperature. Precise control of the temperature of the diode laser and baseplate are essential for the long-term reliable operation of the laser at a specified wavelength. We control temperature by using a thermoelectric element, a sensing thermistor which rests in a small hole close to the diode, and a heat sink which is attached on the top of the laser mount.
In order to frequency scan the laser, we employ a servo loop locking box which maintains the desired frequency by applying a voltage to a pair of piezoelectric transducers which have been soldered back-to-back and placed in between the front plate of the kinematic mount and the horizontal-adjust screw.

Our system has several advantages: 1) low cost, 2) ease of construction, and 3) reliability. All the components in our laser system can be easily made in-house or purchased from vendors.

Saturated Absorption Spectroscopy (SAS)

Saturated absorption spectroscopy (SAS) was first invented in 1972 by Arthur Schalow (1981 Nobel laureate)\textsuperscript{15} and his postdoc Theodor Hansch who won a Nobel prize in 2005\textsuperscript{16}. SAS is a user-friendly method to perform Doppler-free atomic spectroscopy to measure nuclear hyperfine splitting. Besides the fundamental interest, SAS offers an inexpensive, yet reliable method to frequency-lock lasers and is thus vastly used in the fields of precision atomic spectroscopy, laser cooling and atom trapping, and Bose-Einstein condensation, to name just a few.

Optical Setup for SAS of $^{85}$Rb

The weaker output from the non-polarizing beam splitter of the ECDL in Fig.2.1 (a) is passed through a rubidium vapor cell. We tune the laser to an atomic transition by first locking the temperature at $1\sim2$ $^\circ$C below the ambient, holding the current at $\lesssim100$mA, and adjusting the horizontal angle of the diffraction grating in order to tune the laser on resonance (For threshold adjustment, see Ref.$^{17}$). We search for a fluorescent track in the rubidium cell by using the IR viewer, and ramping the PZT so that the laser frequency is continually scanned during the search. In SAS, two weak co-propagating beams traverse through the cell of which one is aligned with a counter-propagating strong beam (see Fig.2.2). This geometry is used to eliminate Doppler broadening. A polarizer is used to reduce the intensity of the laser beam below saturation intensity (for Rb: $2.5$mW/cm$^2$ for
Figure 2.2: Setup for saturated absorption spectroscopy (SAS) reproduce from Soo Y. Kim’s thesis\textsuperscript{18}.

linearly polarized light\textsuperscript{19} to reveal the hyperfine structure of $^{85}$Rb. In our experiment, we use atomic transmission $F_g = 2$ to $F_e = 1, 2, 3$ and $F_g = 3$ to $F_e = 2, 3, 4$ for laser repumping and trapping respectively (shown in Fig.2.3).

### Tapered Amplifier (TA) System

It is well known that ECDLs offer important advantages such as low cost, ease of construction, narrow line width and wide tenability. However, they are limited in output power: After manipulation such as beam shaping, faraday optical isolator, acousto-optical modulator, and fiber coupling, one is typically left with less than 10mW\textsuperscript{20}. The power loss is due to the requirement that the laser output must be in a single spatial mode, which forces the transverse dimension of the diode laser used in the ECDL to be on the order of the optical wavelength. If one want to achieves high power while retaining the narrow linewidth and stability of the ECDL, using tapered amplifier (TA) system is an available method\textsuperscript{21}.

TA devices are available commercially in a price range of $14000-47000$ per unit, depending on whether the ECDL is included or not, and also de-
Hyperfine spectroscopy $^{85}\text{Rb}$ for trapping and repumping respectively. Left is $F_g = 3$ to $F_e = 2, 3, 4$, and right is $F_g = 2$ to $F_e = 1, 2, 3$.

Depending on the choice of maximum output power, center wavelength, and desired accessories, for example, Faraday isolation and/or fiber coupling into and out of the chip.

In our lab, we constructed a homemade TA system at 780nm. Compared to commercial TA devices, the homemade TA is inexpensive as well as compact and stable, the total cost for the TA system (not including the ECDL) is less than $5000. The design and construction of our TA system is described in Jayampathi Kangara’s thesis. (See Fig2.4)

Several steps in alignment are required to be completed before our homemade TA system achieves the desired power for laser cooling and atom trapping.

Before aligning the seed beam from ECDL into the TA chip, we should observe the amplified spontaneous emission (ASE) from the TA chip itself. When we apply some current (less than 500mA) through the TA circuit, ASE emanates from both input and output sides of the device. The ASE emanating from the input end is used to provide a path along which the experimenter can align the seed laser into the TA chip later. However, because this particular adjustment is performed without any seed beam, we are careful not to exceed 800mA to avoid damage to the TA chip. Once we can see
Figure 2.4: The complete TA system, in the graph light enters from the left and exits on the right.

ASE by using IR viewer, we rotate the input side asphere screw to collimate the input side collimating lens so that beam-spot is as compact as possible. The ASE light coming out from the output side of the TA and then aligned through two pinholes for further collimation.

Collimation of ASE should be done as perfectly as possible because the output power depends sensitively on the position of the input side collimating lens with respect to the input facet of the chip. The seed laser is aligned so as to trace the path of the ASE light, through the two pinholes (P1 and P2) (see Fig.2.5) into the TA chip. With the help of two steering mirrors (M1 and M2). A adjustable half-wave plate (H3) is placed in front of the TA to ensure the correct polarization of the input seed laser, as TA output depends sensitively on seed polarization.
Figure 2.5: TA alignment and TA protection circuit schematic layout on the “input” side of the TA chip. In this figure, Anamorphic Prism Pair (APP) is used to circularize the elliptical cross-section of the light beam emanating from the ECDL. The Optical Isolator (FR1) prevents any back reflection into the laser diode. The “shutter” is a part of the TA protection circuit system: The shutter won’t open until the TA current reaches a certain threshold ($\sim 50\text{mA}$).
After finishing alignment on the input side, we also need to do some alignment on the output side (see Fig. 2.6). The ASE emanating from the output end is astigmatic and is collimated only in vertical direction by the output side cylindrical lens (CL). Thus the ASE looks like a horizontal line. In order to ensure the seed mode is coupling into the TA, one can check by observing a bright spot in the center of the horizontal line.

TA chips are notoriously delicate and susceptible to permanent damage by several mechanics, such as voltage spikes across the TA terminal, optical retroreflection, and malfunction in the temperature/current regulation.

To prevent sudden voltage spikes, it is important for the experimenter to ground himself/herself. Optical retroreflection should be absolutely avoided because the backward-propagating laser will produce an excessively high intensity at the narrow input facet which will instantly kill the chip. In our lab we use two Faraday optical isolators (FR2 and FR3s, shown in Fig. 2.6) bought from Conoptics (model number M712B and isolation 37-40 dB) to suppress the retro-reflection, in addition, placing a cylindrical lens with a small angle to prevent any reflection.

A TA protection circuit is also needed in case of malfunction of temperature/current regulation. Running the TA at a high current without a seed beam can lead to thermal degradation of the chip which lead to irreversible damages to the chip if run for several hours without a seed. So the circuit is designed to quickly protect the TA when such things happen. For example,
a shutter automatically blocks the seed laser when the TA current is too low or zero, or disable the TA current controller when the seed laser current drops to near-zero for any reason. To this protection circuit we first deflect a small portion of seed beam to a photodiode by using a glass plate. The photodiode is connected to a current-to-voltage (I/V) converter which feeds in to TA controller (see Fig.2.5). If the seed drops below a certain value, the TA current is safely decreased to zero. Specifically in the lab, we first turn the TA to a safe current, usually 800mA, then block the seed laser and adjust the electronic offset of the I/V converter until the TA current shifts to a lower value. This step places the I/V converter right below the threshold value for the presence of a seed beam. Upon reintroducing the seed beam the threshold is surpassed allowing the TA current to be increased to normal operating values\(^{22}\).

**Acousto-Optic Modulator (AOM)**

For many laser-cooling and atom-trapping experiments, it is necessary to shift the laser frequency on in a very short time scales, \(\sim 1\text{ms}\).\(^{23}\) Acousto-optic modulators (AOM) are widely used to accomplish the laser frequency control. (shown in Fig.2.7).

In our experiment, we use a total of 6 AOMs. Two of these are used to modulate the trap beam and repump beam to achieve a desired laser detuning. Another two AOMs are used in the lattice beam system, one to rapidly switch the laser on and off and the 2\(^{nd}\) for adjusting lattice beam frequency detuning. These four AOMs are used in single pass configuration. We also use two AOMs in double-pass configuration (see fig.2.8) - one with the imaging beam and the second with the pump-probe spectroscopy setup. Compared to single pass configuration, double pass configuration suppresses any spatial shifts due to input frequency modulation. We use several AOMs’ of different makes, so I have condensed information on them in Table.2.1 and Table.2.2.

Note in Table 1. we define 0 MHz as the unshifted (degenerate) \(5^2P_{3/2}\) state, and we lock the trap laser at -0.95MHz (see Fig.2.9). The detuning voltage of trap laser is set based on the test data sheet made by ISOMET technical personnel and the equation which we derived from the data test
Figure 2.7: The basic principles of an AOM is to use the acousto-optic effect to diffract and shift the frequency of the light using sound waves. The sound waves are generated by the PZT attached on one side of AOM’s crystal and the PZT is driven by an oscillating electric signal, the beam interfere with the sound wave and is diffracted into several order.

Table 2.1: Lock point and frequency detuning for each laser, schematic layout for each AOMs setup please see Fig.2.19. The AOM1 used to shift laser frequency to -60MHz, then AOM2 gives it a +100MHz shift which makes the final lattice laser’s frequency at 40MHz. The AOM3 shifts imaging beam’s frequency by +80(2X), since it was shifted -60MHz by AOM1, the frequency end up with 100MHz, which is on-resonance frequency. The probe beam is first shifted by AOM1 and then AOM4 and ended up with 40MHz which the same frequency as the lattice beam. The symbol ‘Γ’ in the table denoted the natural linewidth for Rb(6MHz).
Figure 2.8: In the figure, the beam enters from the top and is steered through a polarizing beam splitter (PBS) into the AOM. Two plano-convex lens (PCX) are set on each side of the AOM in order to focus beam into the AOM crystal. Immediately downstream from the AOM is a quarter-wave plate-mirror combination that reflects the +1 diffracted order back into the AOM, but with orthogonal polarization so that the beam emerges from the left part of the PBS. Thus in order to optimize alignment, if the +1 order diffracted beam is reflected back onto itself through the AOM for a second pass, the +1 order diffracted beam for the second pass will spatially overlap the original beam mentioned in the text the problem of separating residual $0th$ order from the double-passed $1^{st}$ order.

sheet:

\[ Y = 0.2931x - 13.497 \] (2.1)

where \( x \) is the frequency shift and \( Y \) is the voltage detuning.

The lock point and detuning for the repumping beam are not determined by maximizing the signal of the MOT on the monitor camera. To establish the repumping beam lock point, it is not necessary to shift the frequency of the repumping beam, however, it is a necessary side-effect of using the AOM as a switch. The notation “(2X)” in Table 2.1, for the imaging beam and probe beam means they are both in double pass configuration. However, for imaging beam it is not necessary to be double pass, it only needs to be on-resonance i.e. the detuning is fixed at 0 $\Gamma$. For the probe beam the double pass configuration is important because the double pass avoids spatial
modulation of the probe beam during frequency scanning. The notation “-60” in the “AOM Shift(MHz)” column in Table 2.1 means that three beams’ frequencies are shifted by -60 MHz by previous AOM. (Denoted as AOM1 in Fig.2.19)

In Table 2, the reason why there are no serial and model number for the imaging beam and probe beam AOM drivers is because we don’t use the driver offered by the company. We purchased a radio frequency (RF) function generator (Rigol DG 4102, $1200), set the frequency, and fed it into the AOM crystal via a home-made RF amplifier (see Fig.2.10).

### 2.2 Vacuum System

#### 2.2.1 Chamber Design

The vacuum system comprises an ultra-high vacuum (UHV) chamber, and three vacuum pumps of which one is used on a continual basis. We use an 8” stainless steel 26-port extended octagon UHV chamber from Kimball Physics (MCF800-E020080.16) (Fig.2.11). Previously in our old setup, the chamber was evacuated by a 200 L/s Physical Electronics ion getter pump which was cut down by an aperture to only 2 L/s. This pump was heavy and had to be placed on a separate table, and was connected to the chamber with a rigid metal hose which coupled vibration into our experiment. Now we have replaced the 200 L/s pump by a smaller and much more portable ion pump (Fig.2.12), which is fully contained on the optics table enabling us to float the table which significantly reduces the effect of vibrations. Back in

<table>
<thead>
<tr>
<th>Company name</th>
<th>Serial No.(Driver)</th>
<th>Model No. (Diver)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapping beam</td>
<td>ISOMET</td>
<td>26415</td>
</tr>
<tr>
<td>Repump beam</td>
<td>ISOMET</td>
<td>891808</td>
</tr>
<tr>
<td>Lattice beam 1</td>
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<td>26414</td>
</tr>
<tr>
<td>Lattice beam 2</td>
<td>Crystal Tech</td>
<td>11506</td>
</tr>
<tr>
<td>Imaging beam</td>
<td>Crystal Tech</td>
<td>-</td>
</tr>
<tr>
<td>Probe beam</td>
<td>Crystal Tech</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.2: Company name, serial number, and model number for each AOM. Crystal Tech has been bought by Gooch and Housego
Figure 2.9: This figure shows where we lock our trap laser. We first determined the natural linewidth from the oscilloscope using a FWHM measurement of the left most peak for convenience (since the baseline is easy to determine, we can find the half maximum of the left most peak, and then the natural linewidth will also be measured), which is $\sim 18.5$ MHz. Then we lock the trap laser 9.25MHz to the right of the cross over peak between the $F_g=3 \rightarrow F_e=2$ and $F_g=3 \rightarrow F_e=4$ transition.(i.e. at location -0.95MHz)

old building, without floating the table, the MOT was easily destabilized by slight vibration through the ground or accidental bumping on the table.

The residual pressure attainable is in the low $10^{-11}$ Torr range. This new ion getter pump is backed by a refurbished turbo molecular ion pump (Varian V60), which can reach $10^{-6}$ Torr. This pump is then backed by a standard double vane mechanical pump (Varian SD-40), which reaches pressures of $10^{-3}$ Torr. We also ordered new Rb dispensers from SAES Getters Group with a 12mm active length and the model number RB/NF/3.4/12FT10+10. The electric feed-through we ordered is from Kurt J. Lesker Company, model number EFT0074832.
2.2.2 Vacuum Chamber

The first step, before we assemble the chamber from scratch is to make sure all of the components are clean. We start this process by placing the submersible parts (such as small and medium size windows flanges and washers) in an ultrasonic cleaner (made by L&R manufacturing, model number Q210H) with strong soap for about 90 minutes for each run. For big size flanges and washers which cannot fit in our ultrasonic cleaner, we clean one half for about 90 minutes and then clean the other half part for another 90 minutes. The long cleaning time allows the strong soap to remove residual oil from the factory. After the ultrasonic bath the parts are rinsed, first with deionized water, then acetone and finally methanol before wrapping wrapped in oil-free aluminum foil if not inserted into the setup immediately. It is important to avoid contamination of the vacuum system during assembly. We wear powder-free latex gloves and change them often. The inside surface of any vacuum component should never be contaminated by slightest contact with bared skin.

After assembling the chamber, we start to put the three vacuum pumps into the system. We use the combination of roughing pump and turbo pump, connected to the system by all-metal valve to suck out most of the air in the
chamber. These two pumps are turned on at the same time only once. The turbo pump should be run at every 6 months to avoid “pitting” of the ball bearings, to do this we need to turn it on for short period of time just before it runs to the full strength and then turn it off.

   The speed of roughing pump is 0.5 L/s and the turbo pump is 55L/s. At this stage the pressure of the vacuum chamber usually is on the order of $10^{-6}$ Torr and this is the pressure at which it is safe to turn on the ion pump. However, the ion pump, if turned on at this stage, can only reduce the pressure in to the $10^{-7}$ Torr range.

   To take the pressure lower, the next thing is to bake the chamber. We used two layers of aluminum foil to wrap the vacuum chamber, then wrapped heat tape on top. Then, we wrapped a final layer of aluminum foil on top of the heat tape (shown in Fig.2.13). The heating power was set to about
60W. We attained a bake temperature of 200 °C eventually. After a week of continuously baking, the pressure dropped to $9.8 \times 10^{-9}$ Torr.
Next, we asked Jayson Alexander in the instrumentation lab to help us spot-welding the Rb getters onto the pins of an electric feed-through and insert into the vacuum chamber. The Rb getters are a controllable source of Rb vapor. A getter is a strip made of Rb chromates. These chromates are some anhydrous Rubidium metal salts of chromic acid having the formula $\text{Rb}_2\text{CrO}_4$. Rb released when a moderate current of 2 to 6A is run through the device. Special care must be taken with the getters to ensure they will produce a clean Rb vapor, since the getter material can easily absorb water.

After inserting the Rb getters, the vacuum chamber was baked at 200°C
again, and the pressure was observed again to drop to $9.8 \times 10^{-9}$ Torr. However, as mentioned earlier, the ideal pressure should be around of $10^{-10}$ Torr for creating an optical lattice, so $9.8 \times 10^{-9}$ Torr is still too high. We sprayed a small amount of methanol on all the flanges to check for leaks. However, we didn’t see any change on the pressure gauge. We eventually found out the reason why the pressure was high. The first reason is the our digital multiple pump control (MPC) was not well calibrated, which caused some unexpected charge accumulation on the device, leading to wrong data. After MPC calibration, the pressure readout became $6.2 \times 10^{-9}$ Torr. Second, we realized humidity in the lab was a significant. We used a dehumidifier and the pressure dropped to $1.0 \times 10^{-10}$ Torr.

Then we loaded Rb getters into the chamber and turned the current up very slowly until we see a significant increase in the pressure readout. This significant jump means the current are boiling the crud on the getters so that the Rb can release. We saw this jump when our current was at 3.5A, and then we turned the current down to maintain a low pressure inside the chamber. The final pressure is in the range of few times $1.0 \times 10^{-10}$ to few times $10^{-9}$ Torr. This is suitable for forming the MOT and for doing optical lattice and ratchet experiments.

### 2.2.3 Creating and Controlling Magnetic Field

As we know, the cooling mechanism is velocity dependent, but we also need a preferred position for the cooled atoms collect together at. This is
Figure 2.15: Due to the Zeeman Effect, the excited state of a fictitious $F_g=0 \rightarrow F_e=1$ atom has three Zeeman components in a magnetic field, for each of which the energy tunes linearly with position. It is important that the counter-propagating laser beams are orthogonally circularly polarized in precisely the manner indicated for the magnetic gradient shown. Imagine an atom located at $z>0$. Because the $\sigma^+$ light is likely to pump the atom to the $m=1$ exited state, whereas the $\sigma^-$ light is shifted off-resonance from the $m=-1$ state due to the Zeeman detuning, the atom is pushed toward the center of the trap ($z=0$) where the magnetic field is zero. This situation is reversed for an atom located at $z<0$ where the $\sigma^-$ light is more resonant, thus pushing the atom to the right.

achieved with a magnetic field gradient that takes advantage of the Zeeman Effect$^{26}$ (see Fig. 2.15).

As shown in Fig. 2.15 & 2.16 we built two coils, placed on each side of the chamber (we denoted this as the $z$-direction), and let the current, which has same magnitude but opposite direction (i.e. anti-Helmholtz configuration), go through the coils. The symmetrical placement of the coils causes zero magnetic field in the center of the chamber, growing outward. Trapping in MOT occurs because the optical pumping on Zeeman shifted energy levels pushes the cooled atoms toward the region of low magnetic field. Eventually, atoms will be gathered at one spot (where the B-field is minimum), and we use the commercial camera bought from Edmund Industrial Optics (model number: WAT-902C) to focus on that spot to see the atom cloud.
Before beginning experiments on cold atoms, we need to suppress strong dc magnetic fields, due to earth and other nearby sources. For this reason, orthogonal three pairs of magnetic coils, in Helmholtz configuration, are set up centered around the MOT to cancel the strong dc magnetic fields. However, our new ion pump and its vacuum connections necessitated a re-design of our previous Helmholtz coil setup as shown in Fig.2.17. We adjust the current through the 3 pairs individually and at the same time keep turning on and off the MOT’s magnetic gradient to see the atom cloud expansion. We keep doing this until we see the cloud expand symmetrically and slowly in every direction. The complete vacuum system is shown in Fig.2.18.

2.3 Optical lattice & Image Beam and Pump Probe Beam Setup

The lattice laser source just like the trap laser source consist of a TA seeded by an ECDL. The optics setup is the same as the trap beam setup until AOM1 in Fig.2.19, however, the frequency detuning of the lattice beam is significantly farther red-detuned than the trap beam, in order to prevent
Figure 2.17: This figure shows the 3D configuration of the Helmholtz coils used for cancellation of earth’s magnetic field and strong magnetic fields. This 3D model comprises three pairs of coils, the inner pair of which are the smallest coils (0.23 m for each side), the length of the middle pair is 0.48 m, the big coil pair is 0.68 m.
Figure 2.18: These figure show the complete vacuum chamber system viewed from different angles. Each Helmholtz coil-pair for canceling strong magnetic field is formed by first wrapping ribbon-cable (24 wires in ribbon) on the inside of square form stacked in 12-13 layers, and connecting the 2 coils in the pair by 25 pin D-sub connectors as shown in (c).

atomic losses due to spontaneous emission .

A polarized beam splitter (PBS 1) is set in the path of the lattice beam so
that a small portion of the lattice beam emerging from one side of PBS1, can serve as either the probe beam (blue shaded region in Fig.2.19) or the imaging beam. Since the imaging beam should be on-resonance, we set AOM3 in a double-pass configuration. As for the probe beam, the frequency should be the same as the lattice (pump) beam in order to do the pump-probe spectroscopy experiment so the AOM4 is also set in double-pass configuration to scan the frequency without spatial modulation as explained before. The parameters of the AOMs are indicated in Tables.2.1 and 2.2. Fig.2.19 below shows the schematic of lattice system.

Figure 2.19: The experimental layout of the optics necessary to load the atoms into an optical lattice. The blue shaded region are the optics necessary to create the probe beam for pump-probe spectroscopy. Note that we cannot turn the imaging and probe beams both on at the same time.

To create a 1D optical lattice, we use two counter-propagating linearly polarized laser beams $\text{lin} \perp \text{lin}$ to create the polarization gradient. The imaging beam is a circularly-polarized, and retro-reflected. It is important for the imaging beam to be circularly-polarized as the saturation intensity $(1.64\text{mW/cm}^2)$, is lower than for a linearly polarized beam$(2.5\text{mW/cm}^2)$, enabling to scatter more photons/atoms for a given imaging beam intensity.
Lattice and Imaging Laser beams Alignments

The lattice beams consist of counter-propagating, orthogonally linearly-polarized beams passing through a half-wave plate and polarizer (see Fig. 2.20). Here is the check list for lattice beam alignment:\textsuperscript{27}

- Block one of the lattice beams and verify that the unblocked lattice beam is hitting the cold atoms optimally, turn down the intensity and keep optimizing until you can barely see a distinguishable effect.

- Rotate one of the polarizers before the lattice beam enters the chamber, which allows the light from the opposite beam to propagate beyond the polarizer.

- Put an IR card in the path of either lattice beam. One should see two dots on the IR card. Overlap this two dots.

- Using an IR viewer, ensure that light from either beam is coupling into the other beams fiber.

- Rotate the polarizer back to block the light from the opposite beam.

- Using a power meter balance the power of the two lattice beams by rotating the half-wave plate before each polarizer.

\textsuperscript{27}
Figure 2.21: Imaging beam setup on vacuum chamber side. Two lenses after fiber are used to adjust the imaging beam size, so that it can cause the entire trapped atom cloud to fluoresce. Our beam size is about 1cm in diameter.

Imaging beam passes through a polarizer and then $\lambda/4$ plate to make the beam circularly-polarized. Here is the imaging beam setup diagram (Fig.2.21) and check list for aligning the imaging beam:

- Adjust the imaging beam until it hits the cold atoms optimally, turn down the intensity and keep optimizing until you can barely see a distinguishable effect.
- Adjust the retro-reflected light of imaging beam until it coupled back into the optical fiber.
- Rotate the polarizer to change the intensity to $I_{\text{sat}}$.
- Using a IR viewer: rotate the $\lambda/4$ plate until you can no longer see the radiation loss in the fiber from retro-reflection.

2.4 Imaging System

Here we provide a general synopsis of the home-built imaging system. There are multiple methods to measure cold atom dynamics, e.g. pump-probe spectroscopy, Bragg scattering, parametric driving. The most direct method is imaging via a sensitive, fast (short exposure time)
charge coupled device (CCD) camera. In most experiments the CCD is used to observe cold atom expansion as a sequence of short-time exposures, usually less than 1 millisecond. In experiments with optical lattices and ratchets, the CCD tracks changes in the position of the center of mass and the width of the cold atom cloud.

We chose to construct a fast, inexpensive CCD camera system to image the atoms, as the commercial options are prohibitively expensive, for example, commercial options from Princeton Instruments, Andor, etc. cost upwards of $45,000. A reason for the high cost is the low dark current in the cooled CCD chip and the driver software that enables the sequence of precise timing events.

2.4.1 CCD Camera

The ATIK 460ex is chosen to be a desirable CCD camera (see Fig.2.22), for reasons listed below:

*Low dark current and high quantum efficiency* - Active cooling via a thermo-electric Peltier cooling element (TEC) is necessary to reduce the accumulation of thermal electrons thereby increasing the signal-to-noise ratio (SNR). Typically, for cold atom applications, commercial camera systems are cooled down to $< -70^\circ C$ where the dark count rates are $< 0.001 \text{e}^-/\text{px}/\text{s}$ (electrons per pixel per second). For the last reported home-built system, the dark count rate was $< 1 \text{e}^-/\text{s}$. Our system is cooled down to $-5^\circ C$ with a dark count rate of $0.05 \text{e}^-/\text{px}/\text{s}$

*Digital triggering* - Most astronomy cameras operate over a USB connection, therefore, the operating system (OS) must send the exposure command to the camera. There is significant jitter, $\leq 500$ ms in the time-instant at which the OS sends a trigger command to the camera. Much of the back-end software that was developed for this system was to decrease this jitter to 0.5 ms. A digitally triggered camera would save development time.

*On-board processing* - The advantage to on-board processing and a first-in first-out (FIFO) buffer is the ability for the camera to rapidly capture a set of images, where the image separation times are on the order of the
exposure time. The FIFO buffer serves as an on-board memory, allowing the camera to take one exposure and immediately store the image onto the internal memory, thereby enabling the experimenter to image an expanding sample of cold atoms at multiple instants.

Readout noise and large well depth - Readout noise arises from reading out electrical signals via amplifiers and analog-to-digital converters. The ratio of readout noise (and other sources such as dark current, etc.) to well depth determines the dynamic range of the CCD camera. Commercial systems have well depths per pixel of $\sim 200,000 \ e^-\mu m$ with readout noise per pixel of a few $e^-\mu m$. Our system’s dynamic range is about 8X less.

Resolution and Binning - The pixel size determines the resolution of the camera. Many cameras used for cold atom imaging have pixel sizes of tens of $\mu m$. This can be countered by tailoring the lens system, which couples the light into the camera to have a high magnification. The trade-off is a loss in field-of-view. Lower resolution can be achieved by binning several pixels (e.g. bundling an $8\times8$ array of pixels into 1 binned pixel) - this decreases readout time, enabling shorter experimental cycles.

Minimum exposure time $\leq 1\ ms$ - An image is taken by flashing the cold atoms with a resonant light pulse of short duration chosen to be less than the time taken by the atoms to traverse a pixel width, and imaging only during
this short time-window in order to prevent motional blurring. For example, in our case the width for the 8×8 pixel bundle referred to above is 36µm, so a light pulse of width ≤ 1 ms suffices for 10 µK atoms with speeds of ∼ 30 µm/ms.

Computer interface - Our camera interfaces with the computer via USB 2.0, which though universal, limits data transfer (e.g., our experiments are limited to 0.5 Hz). This problem could be addressed using a large FIFO buffer or a faster data transfer protocol (e.g. Firewire, Gigabit ethernet, or USB 3.0).

2.4.2 Two Lenses System and Fluorescent Imaging

In order to image the atoms the light must be focused on the CCD. A standard two lenses system (shown in Fig.2.23) is constructed which use a

![Two lenses system diagram](image)

Figure 2.23: Two lenses system. The first lens is a 2 inches plano-convex spherical lens used to capture all the light comes from the bottom window, and second one is a 2 inches spherical lens used to focus light on CCD.

A lens of focal length 120 mm to capture the light and a 175 mm lens to focus the light onto the CCD. We place the lens immediately under the bottom window to capture as much light as possible. The light intensity coming out of that window can be calculated by using solid angle.

\[
\Omega = \frac{A}{R^2} \quad (2.2)
\]
where Ω is solid angle subtended by area A of the window and R is the distance between the window and the cold atom ball. The fluoresce passes through an infrared filter placed directly against the camera that blocks most of the ambient light. In addition a black box is built around the lens system to further prevent stray light from entering. With both of these light tightening methods we are able to perform experiments with room lights on and see no noticeable difference in the images produced.

2.4.3 LabView, Hardware, Software

In addition to controlling the camera timing for when and how the camera takes an image, cold atom experiments require synchronized turning on and off of magnetic fields and laser beams, and intensity/frequency modulation of optical fields. One may consider using a combination of home-built digital timing circuits and function generators for rudimentary experiments, but a standard astronomy camera is not capable of being triggered by an external TTL pulse. In order to synchronize the camera with a sequence of timed events, we employ two computers arranged in a master-slave configuration, linked via a crossover cable attached to the ethernet ports of both computers. The computers are further linked via a USB DAQ. The USB plugs into the Windows computer and a channel of the shielded BNC connector box is tied to the counter input of the USB card.

The specifications of the master computer are unimportant, save for the fact that it should have a solid state drive (SSD) and enough random access memory (RAM) to enable the creation of a RAMDisk. The most important piece of hardware is the LabVIEW Data Acquisition (DAQ) card from National Instruments (NI). This card allows the transfer of input/output signals in real time to/from a computer. Due to the time scales of interest (the entire experiment may last only few tens of ms during which several different timing-pulses are sent out) the timing of the laser pulses, both when they occur and their width, must have sub-millisecond accuracy. Any NI DAQ card with a clock of greater than 1 MHz and sufficient digital and analog hardware-timed channels will suffice.

One problem we encountered in integrating the camera system with the timing sequences that run the experiment is that the camera system is based
on a computer running Windows 7 for camera driver compatibility. However, Windows 7 is not a real-time operating system (RTOS), hence encounters a problem when dealing with small timescales. Any command sent to the operating system is fulfilled but only after a delay of few hundred ms. This delay is not fixed, varying from shot-to-shot, and is therefore unacceptable for cold atom experiments which typically require pulses at $\mu$s precision.

With help from the Miami University Instrumentation Laboratory, we modified the source code for our astronomy camera. Precise timing is achieved by using a separate Unix-based LabVIEW Real-Time Target (RTT) computer - license-based software. The system consists of two labVIEW VIs running in unison, one on the master computer (Windows), one on the slave (RTT). The communication between the computers consists of a series of checkups and notifications, shown in (see Fig.2.24), that enable the two computers to stay in phase with each other. The front panel of the LabVIEW system is divided into two systems, one that runs the RTT and one that runs Windows, Fig.2.25. All controls for the camera are contained within the Windows LabVIEW VI while the timings are located on the RTT VI. The windows VI allows for a live feed from the camera for alignment but while the experiment is running the data is retrieved in the form of a matrix of intensity values. These values are saved locally (on a RAMDisk) as a text file before being imported into MATLAB by the user for analysis.
Figure 2.25: The top row contains the processes executed by the Windows PC and the bottom row contains the processes executed by the Real-time target. The RTT computer starts a cycle in synchronization with the Windows computer. The Windows computer waits while the RTT starts sending out pulses to the experiment until the time that a command is sent from the RTT to the Windows computer to initiate taking an image. In response the Windows computer sends a command to the camera to take an image. Once the image is taken and saved, the Windows computer waits for a reset command from the RTT computer. This reset command is sent from a counter input channel on a USB DAQ card connected to the Windows computer.
Chapter 3
Data and Discussion

In this chapter section, we show the number, number densities and temperature measurement of trapped cold atoms. Significant improvements have been achieved by comparing with the previous data got in Culler. Other important data such as MOT loading curve, spatial diffusion in optical molasses and track Center of Mass are also discussed and analyzed in the last three sections.

3.1 Atom Number and Temperature Measurement

It is desirable to know just exactly how many atoms are trapped in the MOT. One way to measure the total number of atoms trapped within a MOT is by looking at the fluorescence being emitted from the ballistic expansion of the atom cloud, and this can be done by simply placing a lens and a photodiode outside a window of a chamber.

The photon scattering rate, $R$, for a single atom in a laser field is determined by Eq.3.1

$$R = \frac{1}{2\tau} \frac{I/I_0}{1 + I/I_0 + (2\delta/\Gamma)^2}$$

where $I$ is the trapping beam intensity which is $34\,\text{mW/cm}^2$ (beam diameter is $1.5\,\text{cm}$), $I_0$ is the saturation intensity of the atom which is $1.62\,\text{mW/cm}^2$ for Rubidium, $\tau$ is the Rb atoms excited state life time ($27\,\text{ns}$), and $\delta$ is detuning.
of the imaging beam which is 0 since the imaging beam is on-resonance. Finally we calculated $R = 5.2 \times 10^6$ photon/sec.

The total power emitted per atom per second $P_T$ is given, via the relation

$$P_T = \hbar \omega_a R$$

(3.2)

where $\omega_a$ is the atomic frequency of the $F_g = 3$ to $F_e = 4$ transition for $^{85}\text{Rb}$. For $^{85}\text{Rb}$, $\hbar \omega_a = 2.5 \times 10^{-19}$ J, so that $P_T = 1.3 \times 10^{-12}$ W/atom.

We collect the light from a window which diameter is 3.6cm yielding a solid angle collection $\Omega = 0.046$ steradians. Dividing by $4\pi$, give us collection efficiency, we find that the photon measured over the area of this windows (collection efficiency) is equal to 0.0037 of the total photons emitted by the cloud of trapped atoms.

Multiplying the collection efficiency by $P_T$, we find that the power at the window per atom, $P_w$, is equal to $5 \times 10^{-15}$ W/atom. The gain of the photo diode is $10^7$ V/A, and conversion rate of I/V converter is 0.51 A/W, and power transmission rate L is 0.967, so one can figure out the number of atoms using equation

$$N * P_w * 10^7 * 0.51 * 0.967 = \text{signal in Volts}$$

(3.3)

where the signal (V) is measured by an oscilloscope which is 16.2 V. Plugging V back into Eq.3.3 we can figure out the $N$ (number of atoms) equals $4 \times 10^8$. This is a huge improvement, two orders of magnitude, over the number (~ $1-5 \times 10^6$) in our previous setup in Culler.

Once we have the number of atoms, we can also figure out the number density by measuring the volume of the cloud. We use CCD camera to take pictures of the MOT (the timing diagram is shown in Fig.3.1) and measure the FWHM using MatLab. The volume we found for the atom cloud is $\sim 0.00613$ cm$^3$, which gives the number density $2.31 \times 10^{10}$ atoms/cm$^3$.

Temperature can be calculated by measuring the change in FWHM of expanding cloud once released from the MOT. We analyze the CCD images using Matlab. We measured the FWHM in x and y directions, from 0s to 0.1s in steps of 0.01s. The signal height is presented in Fig.3.2 The expansion
Figure 3.1: This figure shows the timing sequence in atoms number measurement, trap laser is turned off immediately after B-gradient is off. Imaging beam is turned on after trap beam was off for half millisecond. Experimenter can freely choose when to trigger the imaging beam to take a picture at different time. Note: there is 237.5ms delay in the camera start trigger, that’s the delay time of our Windows system to control CCD camera. That’s why you see the camera start 237.5ms before imaging beam is on in the Timing sequence. Imaging beam is turned on for 2ms and but the CCD is exposed time is only 1ms, that will make sure CCD exposure when the imaging beam is on.

speeds in the x and y directions are simply the slopes of these plots. We figure out the temperature by using the equation:

$$\frac{1}{2}mv^2 = \frac{1}{2}k_B T$$  \hspace{1cm} (3.4)

where $k_B$ is Boltzmann’s constant, $v$ is the expansion speed of optical molasses. After we average the temperature in x and y direction, we estimate the final temperature to be $15\sim45 \, \mu$K.
Figure 3.2: From the graph, we see the velocity is the slope for $\text{FWHM}_x$ and $\text{FWHM}_y$. 
3.2 Loading Curve: Verify Background Rb Pressure in Vacuum Chamber

Using the same setup as the number measurement, the loading curve of the trap can be recorded on an oscilloscope. The loading curve can be used to find the background pressure in the chamber. This is an important parameter because the primary reason for the increased trapped atom number and density is that we now have a much higher background pressure to load from than in our previous setup (∼10⁻⁹ Torr now, compare to 10⁻¹⁰-10⁻¹¹ earlier). Therefore we decided to verify the background pressure readout on the ion gauge (∼1.9×10⁻⁹ Torr.)

If we define the loading rate as \( L \), and an elastic collision loss rate \( \gamma_e \), for atoms knocked out of the trap by background gas molecules colliding into them, the following equation may be written

\[
\frac{dN}{dt} = L - \gamma_e N
\]  

(3.5)

When \( t \to \infty \) (steady state), the solution is simply:

\[
N_{ss} = \frac{L}{\gamma_e}
\]  

(3.6)

where \( N_{ss} \) is number of atoms trapped when it reaches the steady state. At early times the number of atoms in the trap is low so the loading rate is only depends on \( L \). Thus, we can find the loading rate by simply drawing a tangent to the curve at early loading time (see Fig.3.3), and equaling the slope to \( L \). From the figure we see the loading rate \( L \) is 0.28 V/sec. The collision/loss rate \( \gamma_e \) can be estimated if we know the value of \( N_{ss} \). In previous section we determined \( N_{ss} \) to be 4×10⁸, so \( L \) is 2.37×10⁸. Therefore \( \gamma_e \) equals 0.59 using Eq.3.6.

But the elastic collision rate \( \gamma_e \) is also be described as

\[
\gamma_e = n\sigma_a v
\]  

(3.7)

where \( n \) is the number density of the background Rb gas, \( v \) is the average velocity of the hot background atoms which is 340m/s at room temperature (T=296K), and \( \sigma_a \) is the atom-atom collision cross-section. For Rb atoms,
the cross-section area for collisions is $2.5 \times 10^{-17} \text{m}^2$. The background number density can be figured out as $6.57 \times 10^{13} \text{atoms/m}^3$. Using ideal gas law $P = n k_B T$ to calculate background pressure $P$ is $2 \times 10^{-9}$ Torr ($2.68 \times 10^{-7}$ Pascals). We find that this pressure is close to the ion gauge readout pressure $1.9 \times 10^{-9}$ Torr.

### 3.3 Spatial Diffusion in Optical Molasses

In this part, we present a experimental investigation of spatial diffusion in optical molasses. As we know optical molasses occur when we switch off the MOT’s inhomogeneous magnetic field (but leave additional magnetic fields on to cancel the earth magnetic field). The motion of the atoms is strongly damped in the “molasses”. The temperature of atoms in optical molasses is much lower than in the MOT.

We made a preliminary measurement of the spatial-diffusion coefficient $D$, and the time scale for atoms to diffusively escape from the molasses. We measured the diffusion constant directly by observing the expansion of a
cloud of atoms with newly setup ATIK CCD camera system\textsuperscript{38}.

We kept the intensity $\sim 34 \text{mW/cm}^2$ (beam power is 60mW measured after $\lambda/2$-plate before splitting into 3 beams), for the cooling laser beams with a detuning of 3.5$\Gamma$. The timing sequence for taking the snapshot of the expanding molasses is shown in Fig.3.1

**Quantitative Treatment**  We took a series of images and analyzed the FWHM to quantitatively investigate the diffusion in optical molasses. We took data at 10ms intervals and averaged over many exposures. We determined the FWHM of the cloud along the x and y axis. We define the cross section for x and y as $(\text{FWHM}_x)^2$ and $(\text{FWHM}_y)^2$ respectively. We also define an average cross-section $(\text{FWHM}_x \times \text{FWHM}_y)$ using the Eq. 3.8.\textsuperscript{38} These cross-section are plotted in Fig.3.4

$$A_{1/2} = 4\pi t D_x \ln(\beta^{-1}) \quad (3.8)$$

where $A_{1/2}$ is the area with the units pixel$^2$ defined by the radius at which the intensity of the image falls to half of its peak value, $D_x$ is the spatial diffusion constant. We extract diffusion constants for $(\text{FWHM}_x)^2$, $(\text{FWHM}_y)^2$ and $(\text{FWHM}_x \times \text{FWHM}_y)$ from the slope of the curves in Fig.3.4. We also measure the diffusion constant at beam power of 55mW and 45mW (see Fig.3.5).

The pixel to cm conversion is given by the magnificent of the lens system in Fig.2.23 and is 0.0064cm/pixel. The diffusion constant in cm$^2$/s are given in Table.3.1 for different laser power.

<table>
<thead>
<tr>
<th>Power</th>
<th>$D_x$ pixel$^2$/s</th>
<th>$D_y$ cm$^2$/s</th>
<th>$D_{xy}$ pixel$^2$/s cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60mW</td>
<td>45753</td>
<td>1.87</td>
<td>31578</td>
</tr>
<tr>
<td>55mW</td>
<td>34803</td>
<td>1.42</td>
<td>25453</td>
</tr>
<tr>
<td>45mW</td>
<td>36373</td>
<td>1.49</td>
<td>36648</td>
</tr>
</tbody>
</table>

Table 3.1: This table shows the diffusion constant at different beam power with the units of pixel$^2$/s and cm$^2$/s.
Figure 3.4: We measured the FWHM of molasses expands linearly in time, indicating that expansion is diffusive. The expansion in the x and y direction, denoted \((\text{FWHM}_x)^2\), \((\text{FWHM}_y)^2\) respectively. We also calculated and plotted \((\text{FWHM}_x \ast \text{FWHM}_y)\).

According to the Eq.3.8, the linear trendline of each plot between snapshots indicate a diffusive expansion. The motion of the atom is diffusive, i.e. the molasses expanding following a Brownian motion.

### 3.4 Tracking Center-of-Mass of Optical Molasses

Calculate center-of-mass (CoM) can help us have a better understanding of the momentum distribution of cold atoms in MOT and optical lattices. We did some analysis using a MATLAB script that calculates the center of mass (CoM) of an atomic cloud.

In this part, we did two different experiments. For the first experiment, we measured the CoM when the magnetic field is well balanced. We prepared a MOT and turned off the magnetic gradient, and allowed the atoms
to thermalize into the optical molasses. Then we turn off the trap laser and repump laser so that the cloud will expend uniformly. After a certain delay, we turn on the imaging beam to make the atomic sample fluoresce and simultaneously expose the CCD. The peak height for the image is presented in Fig. 3.6.

The second experiment is almost the same as the first one except we bias the magnetic field, which is used to cancel the earth’s magnetic field, by changing the voltage on one pair of coils. This leads to the transport of CoM of optical molasses in a preferred direction. We change the voltage from 0V to 5V and 10V respectively, and also change direction to -5V, demonstrate that we can track motion of CoM in both direction. The signal height is shown in Fig. 3.7
Figure 3.5: These two figures show the area of the MOT expanding as a function of time with the trap laser power 45mW and 55mW. The trendline for both figures are pretty linear, and $R^2$ values are very close to 1, which satisfy the Eq.3.8
Figure 3.6: The blue dots and orange dots represents the position of the CoM along x axis and y axis respectively. We took snapshot every 0.01s. We can see even though there are fluctuations, the position of the CoM does not change significantly for the case of a uniformly expanding molasses.
Figure 3.7: We demonstrate the ability to measure the motion of the CoM. Here the motion is induced by biasing the voltage across one of the magnetic field cancellation coils so that it only change the motion of MOT in Y direction. a) shows the CoM_x and CoM_y when the voltage is changed from 0 to 5V. The MOT moves to the -Y direction. b) shows the CoM_x and CoM_y when change the voltage from 0 to 5V (opposite direction) and MOT moves to the +Y direction. C) shows the CoM_x and CoM_y when change the voltage from 0 to 10V and MOT moves to the +Y. Symbol triangle is the uniform expansion in Y direction in Fig.3.6
Chapter 4

Conclusion and Future Outlook

In this chapter, we layout the simulation of 3D optical lattices, and show some experiments we would like to perform such as optical ratchets, observe an anomalous diffusion of cold atoms in dissipative optical lattice and photon counting.

4.1 Future Outlook

4.1.1 Creation of 3D Optical Lattices

Once we have built and characterized the 1D optical lattice (4.1(a)), we would like to move forward to build 3D optical lattices of the type shown in Fig.4.1 (b) and study their properties.

Before we start to build 3D optical lattices, we need to construct models in order to guide our experiment efforts.

With the help of Dr. James Clemens group (group member: Hoseong Asher Lee and Christen Setters), we have simulate preliminary plots of the 3D optical lattices. Figs.4.2 & 4.3 show the potential energy landscape for fixed laser in terms of $3\text{mW/cm}^2$ and two different intersected angles $\theta_x = \theta_y = 20^\circ$ and $54.7^\circ$. 
Figure 4.1: In this figure, (a) is 1D optical lattice configuration, (b) is 3D optical lattice configuration. One can build 3D optical lattices by splitting vector $\vec{k}$ (in a) into $\vec{k}_1$ and $\vec{k}_2$, and splitting vector $-\vec{k}$ (in a) into $\vec{k}_3$ and $\vec{k}_4$; the polarizations of the splitted vector should still be the same as original one. The angle from $z$ axis to $\vec{k}_1$ and $\vec{k}_2$ is $\theta_x$, and the angle from $z$ axis to $\vec{k}_3$ and $\vec{k}_4$ is $\theta_y$. Since the net vector of $\vec{k}_1$ and $\vec{k}_2$ is still $-\vec{k}$, and the net vector of $\vec{k}_3$ and $\vec{k}_4$ is still $\vec{k}$ so configuration in (b) can still produce a polarization dependent well just like 1D lattices. The polarizations of $\vec{k}_1$ and $\vec{k}_2$ in $xOz$ plane are orthogonal to the $\vec{k}_2$ and $\vec{k}_4$ in $yOz$ plane.

4.1.2 Some Experiments on Atomic Motion

Optical Ratchets

Optical Ratchets experiment can be done in either 1D lattices or 3D lattices. Ratchets are also known as Brownian motors. There are devices which "rectify" random fluctuation, turning Brownian motion into directed diffusion, in the absence of net applied bias forces. These devices have been attracting growing attention in number of applications: for example, particle separation, the modelling of molecular motors, and basing nanomachine construction based on biological motor proteins.

Brownian motion exists within an optical lattice as the atoms undergo Sisyphus cooling. There are several type of ratchets - we only consider the rocking ratchet. The basic rule of creating rocking ratchets is that the system must be asymmetric in either time or space and any applied driving forces must be periodic and have a zero-mean (zero-mean AC driving). The
Figure 4.2: The atomic potential energy in the (a) x-y plane and (b) x-z plane for a beam intensity of 3mW/cm² (for each beam), and the intersection angle $\theta_x = \theta_y = 20^\circ$. 

3D Optical lattice, Intensity = 3mW/cm², $\theta = 20^\circ$, X-Y plane

3D Optical lattice, Intensity = 3mW/cm², $\theta = 20^\circ$, X-Z plane
Figure 4.3: The atomic potential energy in the (a) x-y plane and (b) x-z plane for a beam intensity of $3 \text{mW/cm}^2$ (for each beam), and the intersection angle $\theta_x = \theta_y = 54.7^\circ$. 
dynamics of ratcheting effect can be described by Langevin equation:

\[ m\ddot{x} = -\alpha \dot{x} - \frac{\partial U(x)}{\partial x} + F(t) + \xi(t) \]  

(4.1)

where \( F(t) \) is a zero-meaning periodic driving force, \( \alpha \) is the damping coefficient, \( \xi(t) \) is the Gaussian noise (Gaussian noise term has zero-average value), \( U(x) \) is the ratchet potential due to the 1D optical lattice.

To create a rocking ratchet as shown in Fig.4.4 we first need to create

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{figure4_4}
\caption{In state 1 in Figure 4.4, the potential is tilted slightly toward the right for a long time. Next, the system moves toward state 2 where the potential is horizontal. Finally, the potential is tilted significantly but rapidly to the left and brought back up to state 2 in a short time. During this process the atom moves from one well to another, however, the potential remains stochastically in equilibrium.}
\end{figure}

a spatially asymmetric potential by introducing a biharmonic force \((F(t)\) in

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The equation of biharmonic force is:

\[
F(t) = F_0[A_1 \cos(\omega_D t) + A_2 \cos(2\omega_D t + \phi)]
\]  

(4.2)

where \(A_{1,2}\) are amplitudes, \(\omega_D\) is the driving frequency, and \(\phi\) is a relative phase between the harmonics, which controls the symmetry of the system and therefore the generation of a current\(^{43}\). Experimental setup can be accomplished by using the Function/Arbitrary Waveform Generators (Agilent 33250A). The biharmonic waveform is generated on Excel and then loaded into Agilent 33250A using the IntuiLink Waveform Editor. To prevent destruction of optical lattice, we need to adiabatically turn on the driving force, meaning the driving force is ramped up to full driving over some time, which we propose to be 1ms as this is adiabatic (\(\gg \omega_1\)) and a small fraction of the experimental time \(t_e\).\(^{27,44}\) (See Fig. 4.5).

This output signal should be input into the back of the Rigol 4102, and then Rigol can input this signal into AOM and frequency modulate the lattice beam. (shown in Fig. 4.6).

Tsallis distribution and Lévy flight

Besides studying the atomic transport by ratcheting effect, we are also interested in studying the atomic transport properties without any biharmonic
Figure 4.6: This figure looks like Fig.2.10, but the difference between these two is in Fig.4.6 two AOMs are modulating two lattice beams to create a ratchet effect. The detail modulation for ratcheting is described below: a) use frequency modulation input of (AOM) to modulate one of the lattice beams (lattice beam 1), b) another AOM is unmodulated so that the lattice beam (lattice beam 2) maintain at the same frequency.
driving force. As we know, after the cooling process, the atoms in the optical lattice is still interacting with the laser fields, and this motion sometimes cannot be captured by Boltzmann-Gibbs theory. These dynamics usually have large and rare fluctuations yielding broad distributions with power-law tails. A hallmark of these non-Gaussian distributions is the divergence of their second and/or first moment.

Dissipative optical lattices are the ideal test beds to test these non-Gaussian distribution because of their tunability. It is theoretically shown that by changing the lattice’s parameters it should be possible to observe a transition between Gaussian and power-law tail distribution.

In 1D lattice system, under certain approximation (low laser intensity and semiclassical limit), the atomic momentum distribution \( W(p, t) \) satisfies the Fokker-Plank-type equation:

\[
\frac{\partial W(p, t)}{\partial t} = -\frac{\partial [K(p)W]}{\partial p} + \frac{\partial}{\partial p} \left[ D(p) \frac{\partial W(p, t)}{\partial p} \right] \tag{4.3}
\]

and especially in dissipative optical lattice

\[
k(p) = -\frac{\alpha p}{1 + (p/p_c)^2}, \quad D(p) = D_0 + \frac{D_1}{1 + (p/p_c)^2} \tag{4.4}
\]

\( K(p) \) is the drift term, it represents a cooling force (due to Sisyphus effect), \( \alpha \) is damping coefficient, \( p_c \) is the capture momentum. This force acts only on slow particles with a momentum smaller than the capture momentum. \( D(p) \) is diffusion term, it represents the momentum fluctuations and accounts for heating process, \( D_0 \) is constant which stems from the spontaneous emissions and fluctuations in two counter-propagating laser beams, \( D_1 \) is the fluctuations comes from dipolar forces.

Here, we are only interested in stationary solution of Fokker-Plank equation. If we set:

\[
\beta = \frac{\alpha}{2(D_0 + D_1)}, \quad q = 1 + \frac{2D_0}{\alpha p_c^2}, \quad \text{and} \quad U(p) = p^2. \tag{4.5}
\]

we find that \( K(p) \) and \( D(p) \) obey the following relation:

\[
\frac{K(p)}{D(p)} = -\frac{\beta}{1 - \beta(1 - q)U(p)} \frac{\partial U(p)}{\partial p}. \tag{4.6}
\]
which means that the stationary solution \( W(p) \) of the Fokker-Plank equation is the Tsallis distribution defined by

\[
W(p) = Z_q^{-1}[1 - \beta(1 - q)U(p)]^{1/(1-q)}
\]

(4.7)

where the constant \( Z_q^{-1} \) is a normalizing factor. For \( q \to 1 \), the stationary solution (Eq.4.7) reduce to Gaussian distribution. However, if \( q > 1 \), anomalous diffusion takes place. For optical lattices, the index \( q \) can be written as \( q = 1 + 44E_R/U_0 \), where \( E_R \) is the recoil energy and \( U_0 \) is the potential depth of the optical lattices wells. Thus we can observe a transition between Gaussian and Tsallis distributions by varying the depth of the optical lattice.

### 4.1.3 Polarization-Selective Intensity Correlations

Intensity correlation measurement (ICM) of light was first demonstrated by Hanbury Brown and Twiss in 1956. Nowadays, this measurement has numerous applications in the field of optics, nuclear physics, and cold atoms.

The intensity correlation, or second order correlation \( g^{(2)} \) is defined as:

\[
g^{(2)}(\tau) = \frac{\langle \hat{I}(t)\hat{I}(t+\tau) \rangle}{\langle \hat{I}(t) \rangle^2}
\]

(4.8)

where \( I(t) \) is the intensity from radiating atoms at the time \( t \), and \( I(t+\tau) \) is the intensity of the radiating atoms at the time delayed by \( \tau \).

As we known, the atoms in the optical lattice are still interacting with the laser fields therefore undergo spontaneous emission which leads to hopping from one potential well to another (see Fig.4.7). The atom emits a \( \sigma^+ \) or \( \sigma^- \) photon depending on which polarized light it interacts with.

In order to track atomic transport by measuring the dwell time and cross over time (please see description in Fig.4.7), we propose to build an apparatus to detect the photon correlation and measure the intensity correlation. Fig.4.8 shows an outline of the setup for the intensity correlation measurement.
Figure 4.7: This figure shows atoms hopping around in a 1D optical lattice. The $\sigma^+$ and $\sigma^-$ polarization light shows up at alternate potential well sites. If, in a simple case, we consider one atom is interacting with $\sigma^+$ light, this atom will spontaneously emit a $\sigma^+$ photon and then jump to either the joint $\sigma^-$ well or jump back to the same $\sigma^+$ well. 1) For the first case, in which the atom jump to the adjacent $\sigma^-$ well, the photon detector will detect a $\sigma^+$ followed by a detection of a $\sigma^-$ photon some time $\tau_1$ later. $\langle \tau_1 \rangle$ is a measure of the cross over time between adjacent wells in lattice. 2) If the atom stay in the same well, the detector will detect a $\sigma^+$ photon followed by detection of another $\sigma^+$ photon some time $\tau_2$ later. $\langle \tau_2 \rangle$ is a measure of dwell-time in a particular well of the optical lattice.

We first propose to build a multichannel coincidence-counting module (CCM) based on D.Branning’s design. In his paper, he presents a method to build a multichannel CCM with off-the-shelf integrated circuit components, and the cost is less than $600. However, after discussing with Mike Weeks from the Miami University Instrumentation Laboratory, we figured out that the same device can be built even more simply for even less cost by using a Myrio.

### 4.2 Conclusion

In conclusion, we have setup trapping and cooling laser system and vacuum system in our new lab. We have created the MOT and shown promising data on atoms number measurement in the MOT. We have checked the validity of our FWHM measurement by calculating the temperature of our atomic sample. We have setup the 1D lattice, and hope that lattice experiments will
Figure 4.8: Schematic for measurement of dwell time and cross over time in optical lattice. In this figure, the emitted $\sigma^+$ & $\sigma^-$ photons are converted to linear after passing through the $\lambda/4$ plate, and directed by the PBS placed after $\lambda/4$ plate is used to separate the to separate Single-photon counting detectors. The signals will be sent to coincidence-counting electronics, and then the output data will be sent to a computer where the counts are collected, integrated, displayed and stored to disk via freely available software\textsuperscript{52}.

be started soon.

Significant improvements have been achieved after moving into the new building:

- We have setup the main laser system and vacuum system on separate floated tables. These contribute to long-time stability of cold atom sample, and considerably ease the life of the experimenter.

- The vacuum system and Helmholtz coils for strong magnetic field cancellation are much more compared than before.

- The number of trapped cold atoms is two order of magnitude higher, up from $\sim 5 \times 10^6$ atoms in our previous setup to , but we have $7 \times 10^8$ atoms now.
• The number density is two orders of magnitude higher $2.31 \times 10^{10}$ atoms/cm$^3$ now compared to $2 \times 10^8$ atoms/cm$^3$.

• The temperature of the cold atoms is below $15-45 \mu K$, colder than our earlier temperature of about $100 \mu K$ achieved in the previous setup.

Our newly achieved trapped atom numbers, number densities, and temperature are sufficient to enable optical lattice and ratchet experiment described in previous chapter$^{53,13,11}$.
Chapter 5

Publications and Presentations

Publications


Presentations

“Ultracold Atoms in an Optical Lattice: Controlling matter on the Nano-Scale,”
Shan Zhong, and Dr. Samir Bali
Miami University Graduate Research Forum (2014).

“Investigating Cold Atom Transport in Optical Lattices and Ratchets” Shan Zhong, Ethan Clements, Zach Pollock, Anthony Rapp, Preston Ross, Andre Hachtel, Samir Bali - We experimentally investigate cold atom transport in optical lattices and ratchets in an undergraduate setting using home-built laser and imaging systems. It is well-known that the transport properties exhibited in these situations by ultracold atoms depart from the usual framework of Boltzmann-Gibbs statistical mechanics. We describe methods to quantify these departures by tracking the atomic momentum and spatial distribution, and measuring the “dwell time” and “crossover time,” respectively, in a particular well and between wells. - Poster, 46th Annual Meeting
of the APS Division of Atomic, Molecular and Optical Physics Volume 60, Number 7.

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