

QUANTUM INTERFERENCE SPECTROSCOPY WITH RUBIDIUM

by

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Abstract

A recent powerful spectroscopic technique that has been implemented using femtosecond lasers excites atoms or molecules through quantum interference effects. The results are oscillations in excited state populations that represent the optical frequencies used in the excitation pathway, these frequencies can be found by Fourier analysis. The technique uses a Mach-Zender interferometer wherein one femtosecond pulse is split into two pulses that are phase coherent. These pulses are the pump and probe pulses which are delayed with respect to one another by a variable time. During the delay between pulses the state excited by the first (pump) pulse evolves in time before the probe pulse is used to excite the atom into its final state. The observed final state population exhibits interference between the several possible pathways to the final state. The information gained from this method will allow for advances in other processes such as the dynamics of photo-association.

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Dedication

To my mom and dad. Thank you for your support.

CHAPTER 1 - Introduction

The technique we want to explore is one of high precision spectroscopy that could be applied to a molecular system, such as one created through the process known as photoassociation. The results of the experiments described here will allow us to verify the feasibility of using this high precision spectroscopy.

The basic idea behind the spectroscopic technique is to do a pump-probe measurement. That is, a single pulse is split into two pulses; the first excites a transition (one- or two-photon), and the second completes the excitation. A measurement of the interference between the two excitation pathways is then a direct measurement of the energy difference between the intermediate states.

In the test system that is being explored, we are studying the interaction between the $5s_{1/2}$ - $5p_{1/2}$ - $5d_{3/2}$ and $5s_{1/2}$ - $5p_{3/2}$ - $5d_{3/2}$ excitation paths in atomic Rb. In our specific case, the pump-probe consists of one KLS (Kansas Light Source) pulse split into two pulses of equal intensity using a Mach-Zehnder interferometer. The phase relationship between the two pulses is fixed. The first pulse is our pump pulse, and the second pulse is delayed in time (τ) and is our probe pulse. Each pulse is of about 10 fs in temporal length and has its wavelength centered around 800 nm. The delay between pulses allows the state excited by the first pulse to evolve in time. Then, the second pulse is used to further excite to the state we want to detect. The delay time between pulses is controlled by the difference in path length between the two arms of the interferometer.

The motivation for using this technique is that the beat oscillations in our data tell us the structure in the system we are studying. In this test system, this is the fine structure splitting in the 5p levels of Rb. The measurement of the structure will identify the excitation pathways we are making use of in future systems of interest. For example, this information could be useful if you were trying to produce molecules using multiphoton photoassociation. Because the modulation of the beat would not only tell you which levels were being excited but also their yield, one could do a Fourier transform across the entire delay time, and obtain frequencies that are involved in the excitation. This information could then be used to enhance the production of

molecules through photoassociation by choosing a delay for which we obtain constructive interference.

In the test system we are interested in here, the rubidium atom can be excited to many different levels. The laser that is used in the excitation process produces pulses that contain frequencies of 800 ± 50 nm. These laser frequencies allow for the excitation of all of the fine-split 5p-states and 5d-states. For the atom to be excited into the state we will detect (the 5d), the atom must absorb two photons. The atom can either absorb two photons from the first or second laser pulse, or absorb one photon per pulse. Either way, the atom's wave function will be able to evolve in time after the first pulse(s) photons is/are absorbed. It is this time delay between pulses which allows for a quantum interference effect, in which the atom can take two different temporally distinct excitation path ways to arrive at the same final state. These different pathways will lead to oscillations in our data corresponding to the different frequencies used in the excitation of the atom to its final state.

The bulk of this document is dedicated to the setup of the interferometer since this is what took the most of the experimental time. This document should serve as a blue print for future students working on the continuation of this project.

CHAPTER 2 - Theoretical Considerations

To produce the desired results, this experiment relies on a quantum interference effect, where the atom is excited via two energetically different pathways to end up at the same final state. Looking at Fig 2.1 we can see the different excitation pathways. For one pathway the excitation is from the ground state ($5s_{1/2}$) to the first excited state ($5p_{1/2}$) and then to the final state ($5d_{3/2}$); the second pathway is from the ground state ($5s_{1/2}$) to the second excited state ($5p_{3/2}$) and then to the final state ($5d_{3/2}$).

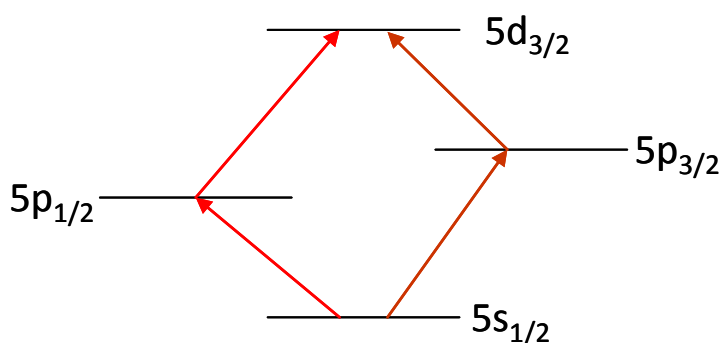


Figure 2.1 Excitation pathways of Rb atom from ground state to final state

For a Rubidium atom to be excited from the ground state ($5s_{1/2}$) to either the first ($5p_{1/2}$) or second ($5p_{3/2}$) excited state, it must absorb a photon whose energy is equal to the energy difference between the two states. The energy difference between states is usually given in electron volts (eV), but for this discussion it may be more useful for us to use the wavelength (λ) of the corresponding transition. The bandwidth of the laser pulses contains all the wavelengths needed for these excitations to occur. The laser pulse has a central wavelength of 800 nm and has a spectral width of >100 nm. The relationship between energy (E) and wavelength (λ) is given below where h is Planck's constant and c is the speed of light.

$$E = hc / \lambda$$

In Table 2.3 the wavelength, energy, frequency and wavenumber for each atomic transition are listed.

	Wavelength (nm)	eV	Frequency (MHz)	cm ⁻¹
5p _{1/2} -5s _{1/2}	794.9789	1.560	377368506.3	12578.95021
5p _{3/2} -5s _{1/2}	780.2414	1.589	384496387.9	12816.54626
5d _{3/2} -5p _{1/2}	762.10304	1.627	393647557.2	13121.58524
5d _{3/2} -5p _{3/2}	776.15716	1.597	386519737.6	12883.9886

Table 2.1 Values for atomic system (<http://www.physics.nist.gov/cgi-bin/ASD/lines1.pl>)

As Figure 2.1 shows, it takes two photons for us to reach our final state (5d_{3/2}). Using an interferometer allows us to take a single laser pulse and create two identical laser pulses of equal phase and amplitude, these two pulses are the “pump” and “probe”. Because we are using two identical pulses, we are allowed to use the same wavefunction for each excitation of the rubidium atom which makes our calculation simpler. These pulses are delayed by a fixed amount of time equal to the path difference of the two legs of the spectrometer divided by the speed of light. The importance of this delay is that it allows the atomic state to evolve in time before being excited by the second pulse. Below is an expression for the excitation from the ground state into all possible states that are considered in this model allowed from the first pulse.

$$|5s_{1/2}\rangle \rightarrow \left(1 + c_{s_{1/2},s_{1/2}}^{(2)}\right)|5s_{1/2}\rangle + c_{p_{1/2},s_{1/2}}^{(1)}|5p_{1/2}\rangle + c_{p_{3/2},s_{1/2}}^{(1)}|5p_{3/2}\rangle + c_{d_{3/2},s_{1/2}}^{(2)}|5d_{3/2}\rangle$$

The first term in the sequence says that the target atom is in the ground state (5s_{1/2}). The arrow represents the first pulse interacting with these target atoms in the ground state. The next term says that after the first pulse interacts with our target, there is some amplitude that nothing happens and that is represented with a number one, or a two photon process could occur where the atom is excited from the ground state (s_{1/2}) into an excited state (p_{3/2}, p_{1/2}) and then a second photon de-excites that atom back down into the ground state (s_{1/2}). This two photon process is

represented using a coefficient with the subscript ($s_{1/2}, s_{1/2}$) and a number two in the superscript to represent the two photons. Looking at the next term in the sequence for the $5p_{1/2}$ state, here the subscript of the coefficient is ($p_{1/2}, s_{1/2}$) and a number one (1) is in the superscript to indicate that a single photon is used in the excitation of the atom from the $5s_{1/2}$ into the $5p_{1/2}$. The next term in our series for the $5p_{3/2}$, is similar to the second term where a single photon excites the atom into the $5p_{3/2}$ excited state and the coefficient represents this with a similar subscript ($p_{3/2}, s_{1/2}$) and superscript (1). The last term in the series is for the $5d_{3/2}$, which is our final state. Here also we see that it takes a two photon process to get our atom into this final state. This is represented using a coefficient with a subscript indicating the atom travels from the ground state ($s_{1/2}$) to either of the $5p$ states and then into the $5d_{3/2}$ state ($d_{3/2}, s_{1/2}$). The value of the two photon coefficients is tempting to be approximated as zero using a weak field approximation because the interaction with the electromagnetic field isn't very strong. But, this is inconsistent with our result that a two photon process is needed to arrive at our final state.

These coefficients are for the time-dependent states that we get by solving the time-dependent Schrodinger equation starting with $5s_{1/2}$. We could represent these coefficients as $\langle \beta | U(T) | \alpha \rangle$ where $U(T)$ is a unitary time evolution operator determined by the pulse. In general, this unitary operator is equal to one plus terms involving all powers of the electric field in the pulse. Since the electric field is weak we only need to consider the lowest powers of the electric field. For example, the integral for $c_{\beta\alpha}^{(1)}$ is:

$$c_{\beta\alpha}^{(1)} = \langle \beta | U(T) | \alpha \rangle = \delta_{\beta\alpha} - \frac{i}{\hbar} \langle \beta | -ez | \alpha \rangle \int_0^T E(T) e^{i(E_\beta - E_\alpha) \frac{t}{\hbar}} dt.$$

The result of the integration is a Fourier transform from the time domain to the frequency domain, such as:

$$\tilde{E}\left(\frac{E_\beta - E_\alpha}{\hbar}\right) \cong \tilde{E}(\omega_{\beta\alpha}).$$

An example of one of the coefficients that we are using in our calculation looks like this.

$$c_{p_{1/2}, s_{1/2}}^{(1)} = -\frac{i}{\hbar} \langle 5p_{1/2} | (-ez) | 5s_{1/2} \rangle \int_0^T E(T) e^{i[E(5p_{1/2}) - E(5s_{1/2})] \frac{t}{\hbar}} dt$$

Now, before the second pulse arrives, there is a delay in time (τ) which allows the state to evolve in time by an exponential term.

$$e^{-iE_{s_{1/2}}\tau} \left(1 + c_{s_{1/2}, s_{1/2}}^{(2)} \right) | 5s_{1/2} \rangle + c_{p_{1/2}, s_{1/2}}^{(1)} e^{-iE_{p_{1/2}}\tau} | 5p_{1/2} \rangle + c_{p_{3/2}, s_{1/2}}^{(1)} e^{-iE_{p_{3/2}}\tau} | 5p_{3/2} \rangle + c_{d_{3/2}, s_{1/2}}^{(2)} e^{-iE_{d_{3/2}}\tau} | 5d_{3/2} \rangle$$

Now that we have an expression for the time evolved wave function, a second pulse interacts with our system. The result of the second pulse affects each term in the time evolved wave function by multiplying them by another set of coefficients. The coefficients represent the amplitude that the atom makes a transition from the state it's currently in to whichever state it is excited to. The only state that we are interested in calculating is the final state that we measure, which is the $5d_{3/2}$. Collecting these terms we have the following expression:

$$\left[c_{d_{3/2}, s_{1/2}}^{(2)} e^{-iE_{s_{1/2}}\tau} + c_{d_{3/2}, p_{1/2}}^{(1)} e^{-iE_{p_{1/2}}\tau} c_{p_{1/2}, s_{1/2}}^{(1)} + c_{d_{3/2}, p_{3/2}}^{(1)} e^{-iE_{p_{3/2}}\tau} c_{p_{3/2}, s_{1/2}}^{(1)} + c_{d_{3/2}, s_{1/2}}^{(2)} e^{-iE_{d_{3/2}}\tau} \right] | 5d_{3/2} \rangle.$$

Examining this expression from left to right, the first term indicates that the first pulse does not excite the atom but leaves it in the ground state ($s_{1/2}$), the atom evolves in that state, and then the second pulse excites the atom into its final state ($d_{3/2}$) through a two photon process. The next two terms are similar in that they both involve the atom being excited from the ground state ($s_{1/2}$) into a p-state ($p_{1/2}, p_{3/2}$), evolving in that p-state, and then being excited by the second pulse in the final state ($d_{3/2}$). Our last term says that the first pulse excites the atom via a two photon process from the ground state ($s_{1/2}$) into its final state ($d_{3/2}$), the atom is allowed to evolve there, and then stays in that excited state after the second pulse has acted.

We now take the square of this coefficient to find the probability that the atom will take these pathways to its final state. This probability has many terms corresponding to possible values of $(E_\beta - E_\alpha)$. One of the more interesting terms is the interference that occurs between the two p-states ($p_{1/2}, p_{3/2}$).

$$\begin{aligned}
& c_{d_{3/2}, p_{1/2}}^{(1)} c_{p_{1/2}, s_{1/2}}^{(1)} c_{d_{3/2}, p_{3/2}}^{(1)*} c_{p_{3/2}, s_{1/2}}^{(1)*} e^{-i(E_{p_{1/2}} - E_{p_{3/2}})\tau} + c_{d_{3/2}, p_{3/2}}^{(1)} c_{p_{3/2}, s_{1/2}}^{(1)} c_{d_{3/2}, p_{1/2}}^{(1)*} c_{p_{1/2}, s_{1/2}}^{(1)*} e^{-i(E_{p_{3/2}} - E_{p_{1/2}})\tau} \\
& |c_{d_{3/2}, p_{1/2}}^{(1)} c_{p_{1/2}, s_{1/2}}^{(1)} c_{d_{3/2}, p_{3/2}}^{(1)*} c_{p_{3/2}, s_{1/2}}^{(1)*}| (e^{-i(E_{p_{1/2}} - E_{p_{3/2}})\tau} + e^{-i(E_{p_{3/2}} - E_{p_{1/2}})\tau}) \\
& (e^{i(E_{p_{3/2}} - E_{p_{1/2}})\tau} + e^{-i(E_{p_{3/2}} - E_{p_{1/2}})\tau}) = 2 \cos[(E_{p_{3/2}} - E_{p_{1/2}})\tau]
\end{aligned}$$

The beat frequency between the $5p_{3/2}$ and $5p_{1/2}$ state is determined using the period of the cosine term and then solving for the delay.

$$\begin{aligned}
\frac{(E_{\beta} - E_{\alpha})\tau}{\hbar} = 2\pi &\Rightarrow \tau = \frac{2\pi\hbar}{E_{\beta} - E_{\alpha}} \Rightarrow \tau = \frac{2\pi\hbar}{Ep_{3/2} - Ep_{1/2}}, \\
= \frac{1}{ck} &= [(237.596 \text{ cm}^{-1})(3 \times 10^{10} \text{ cm/s})]^{-1} = 0.140 \text{ ps}
\end{aligned}$$

where k is the energy difference expressed in wavenumber.

The pulse of the laser we are using contains each frequency that is needed for excitation to occur. This means beating will occur for each level and that there will be a beat for the difference of these levels also. To find these beating terms we need to write out the entire expression to see exactly what's happening.

$$\begin{aligned}
\text{probability}(\tau) = A_0 + A_1 \cos\left[\left(E_{d_{3/2}} - E_{s_{1/2}}\right)\frac{\tau}{\hbar} + \phi_1\right] + A_2 \cos\left[\left(E_{d_{3/2}} - E_{p_{3/2}}\right)\frac{\tau}{\hbar} + \phi_2\right] + A_3 \cos\left[\left(E_{d_{3/2}} - E_{p_{1/2}}\right)\frac{\tau}{\hbar} + \phi_3\right] \\
+ A_4 \cos\left[\left(E_{p_{3/2}} - E_{p_{1/2}}\right)\frac{\tau}{\hbar} + \phi_4\right] + A_5 \cos\left[\left(E_{p_{3/2}} - E_{s_{1/2}}\right)\frac{\tau}{\hbar} + \phi_5\right] + A_6 \cos\left[\left(E_{p_{1/2}} - E_{s_{1/2}}\right)\frac{\tau}{\hbar} + \phi_6\right]
\end{aligned}$$

Here all the constants and coefficients have been absorbed into the “A” terms and A_0 is a constant independent of time. Looking at term A_1 we calculate an oscillation of 61 fs, which is far too fast to be observed. Our A_4 term was in our example above and was calculated to be 0.14 ps. The remaining four terms, A_2 , A_3 , A_5 , and A_6 will oscillate near the laser frequency, we find them to be 2.587 fs, 2.540 fs, 2.601 fs, and 2.650 fs respectively. Since these frequencies are so

close together, we will also see beats between the differences of their frequencies. Looking at the beating between the A_3 and A_5 terms, for example, we get a beat frequency with a period of 109 fs.

Our data should reflect the excited state population as a function of τ . The Fourier analysis of this data should show the frequencies in the expression above. This kind of beat structure in the probability has been observed by Mudrich [1] in a somewhat different experiment and this is what we hope to see as well.

CHAPTER 3 - The Experimental Setup

A Mach-Zehnder interferometer consists of many components. The laser beam originates from a Ti:Sh SYN-PRO oscillator which produces a 800 nm beam that repeats at 75 MHz. The spectral width of the beam is >100 nm at full width half maximum (FWHM). The beam then is directed through a series of mirrors to a Galilean telescope which is designed to reduce the beam waist by 50% as well as to collimate the beam. The Galilean telescope consists of two lenses, the first lens (L1) is the objective lens and is convex-convex and the second lens (L2) which is the eyepiece is convex-convex. The objective lens has a focal length of 10 cm and the eyepiece has a focal length of -5 cm. The two lenses were positioned along the beam line, where the objective lens was fixed to the table and the eyepiece was on a translation stage (TS) so that it could be moved to find the optimal separation distance between the two lenses and reduce the beam divergence as much as possible. Using a telescope equation $d = f_o + f_e$ [2] where d is the separation between the two lenses in the telescope and f_o is the objective focal length and f_e is the eyepiece focal length, the separation distance is 5cm. This was approximately correct but due to changes in beam size and position, the telescope needed to be adjusted on a day to day basis. To find the initial separation distance needed, a set of mirrors was introduced before the transport line that reflected the beam back and forth inside the Kansas Light Source (KLS) room where the oscillator is stored. The total path length of the beam was measured to be approximately 14 meters which is roughly the same as the distance the oscillator to the experiment. This was done so that the beam diameter could be measured from within the room that the translation stage was being operated. Once the translation stage was positioned so that the beam's diameter could no longer be reduced, the mirrors were removed from the setup, and the beam was then directed up through an evacuated transport line which carries the beam approximately 14 meters to the bread board where the interferometer is set up. Because we are using a Galilean telescope in this manner, the beam size was found to be reduced. The magnifying power (MP) of this telescope can be found using this equation $MP = -f_o/f_e$ [2], and putting in our values for the two focal lengths we have a magnifying power of 0.5, which means that the beams diameter should be reduced by half or 50% of its original size. The beam's diameter was measured to be 25mm,

where some of the beam was lost off the edges of the mirrors themselves. Inside the transport line there are 3 mirrors which are adjusted via mechanical actuators that are controlled using a servo controller and remote. The beam inside the transport line could be viewed using three CCD cameras which displayed an image on a pair of monitors of the beam reflecting off the mirrors inside the transport line. The beam was always centered on the mirrors, and an iris was used right after the oscillator to locate the most intense part of the beam. That iris was then closed so that it only allowed the most intense part of the beam to pass through. The final mirror was controlled without the use of a monitor, but by using an infrared card that showed where the beam was exiting the transport line. The final mirror was adjusted so that the beam was directed onto a mirror on the breadboard that changed the propagation of the beam from vertical to horizontal. This breadboard is where the interferometer was build and has the dimensions 28" x 20 1/16", and is made of solid cast aluminum. Initially, when the beam exited the transport line a position was found on the breadboard where the beam was exiting in the exact center of the Brewster window of the transport line. This was done by walking the beam to its furthest x-y directions. By doing this, a circular pattern was made on the breadboard which was traced out using a pencil on the breadboard itself. Then the center of that circle was taken to be the center of the transport window. That was found to be 7.8cm from the bevel on the edge of the south side of the board or 8cm from the edge of the south side of the board. This same distance from the edge of the south side was measured all the way down to the west side of the board, this was the direction the beam would initially propagate. Then irides were placed along this line along with a CCD camera so that the mirror (M1) could reflect the beam along this line. Once this line was found, it served as the basis for the reproducibility of this experiment.

The most important part of setting up an interferometer is reproducibility. Without being able to reproduce the same result day after day, the amount of time and effort that is needed to set up the interferometer outweighs its usefulness. For reproducibility to occur, what you need are straight lines. But, what do you need to produce a straight line? A straight line is any line that connects two points in space. Okay, but when setting up an experiment, not any old straight line will do. You need not only straight lines but straight lines that can be found in the same exact place each time. And, these lines generally aren't just lines drawn on the bread board the experiment rests on; they're laser beams that make up our straight lines. But, this breadboard offers a few advantages. Across the bread board there are holes that are spaced 1" from

each other and $\frac{1}{2}$ " from the edges of the board. These holes have been machined so that they form a straight line. This is great, we have straight lines now, but that's not the whole story. The optics we have to place on this board have to sit inside optical mounts that have to be placed on the board. So how do we put the optics on the board so that they sit right on top of the holes that form a straight line, so that we also have beams that form straight lines? Well, the main optic we are using to form straight lines are irides. Each iris, when closed, has a 0.8mm diameter and when fully open is 25mm in diameter. These irides have a #8-32 screw located directly below the center aperture, which screw into the top of pedestal pillar posts which has a hole of corresponding size on the top. The hole in the post is directly in the center of its diameter. The pedestal pillar posts for the irides stand 4" high and are 1" in diameter and a $\frac{1}{8}$ " thick spacer that is also 1" in diameter sits between the iris and the post. The 4" posts and $\frac{1}{8}$ " spacers are made of solid stainless steel; they were chosen to reduce any vibrations the optics on the breadboard may experience. What we want to do is place the posts directly above each hole in the breadboard. If these posts are positioned slightly off center of the holes, then we won't be able to reproduce the same straight lines. So, how do we do this? On the bottom of the 4" posts there are #8-32 holes, but the holes in the breadboard are for a $\frac{1}{4}$ "-20 size screws, which may appear to be a problem since the hole sizes don't match, but we have hybrid screws that go from the $\frac{1}{4}$ "-20 size to the #8-32 size. Here are the steps needed to efficiently complete the process of placing iris so that it can form a straight line. First, the #8-32 side of the hybrid screw needs to be screwed into the 4" post. Once this is done, the post now needs to be screwed into the table (Fig 3.1(a)). What you are going to notice is that once the post is screwed in the table the iris may be at some angle to the beam propagation. This is not a worry because the post will not be kept in this position long, this is simply to mark the position of the post on the breadboard. To mark the post's position on the breadboard, we are going to use fixed kinematic stops. Using two of these stops will be adequate and should be positioned maximally 90 degrees apart on the base of the post. To position the stops, you need to bring the ball of the stop in full contact with the base of the post, and then fix them in that position by screwing them to the breadboard. If there are no holes available on the breadboard to screw the stop down to, a breadboard clamp can be used to secure the stop down with. Once the stops have been screwed firmly to the table, you need to check to see if you can get the clamping fork around the base of the post. In some cases you will find that there is no position available to screw down the clamping fork due to other optics being located

in its space (Fig 3.1b). If that is the case, you will need to reposition either one or both of the stops until all three devices can be placed around the base of the post (Fig 3.1c). Once all three devices have been placed, you need to remove the clamping fork and unscrew the post from the breadboard. Many times the hybrid screw will remain in the table instead of remaining in the post. To remove the hybrid screw from the table or post, it is recommended you use a pair of pliers with duct tape wrapped around the pincers of the pliers. The duct tape is necessary so that the threads on the screw are not stripped off. If the screw does not remain in the table, you need to remove it from the base of the post. Now the post must be replaced back to breadboard in the position the two stops have marked. Using the clamp, secure the post to the table and remove both stops from the table (Fig 3.1d,e). You can use your eye to determine that the face of the iris is positioned in the direction of the beam propagation.

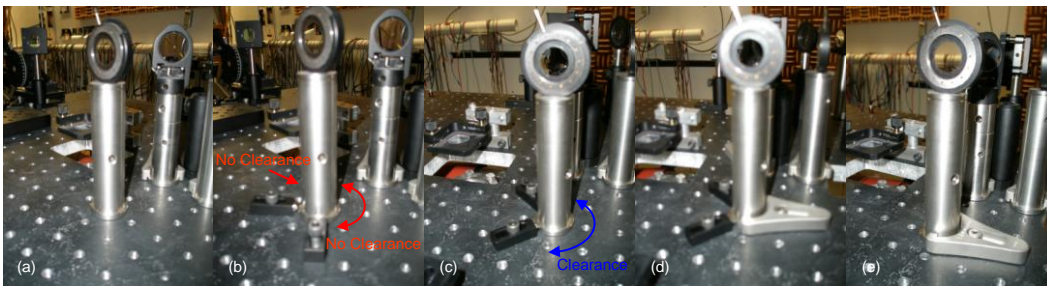


Figure 3.1 Procedure for setting up an iris

Now that you have one iris in position, you can repeat this technique with a second iris on the table that is directly down the same line of holes on the breadboard, this should create a straight line. Also, each of these post/spacer/iris combinations are the same height, reducing the difficulty of this alignment by one variable, that is the z-axis. At this point it may appear that you can use an IR-card and your eye to tell if the beam is passing through the smallest openings of the irides, but this is not the case. The interferometer is such a high precision device, that we must go one step further, we must use a CCD camera. When a beam passes through a small circular opening of the iris we get Fraunhofer diffraction [2] which produces an Airy disk pattern that can be seen on a CCD camera's display. But, any part of the beam passing through the center of the iris will produce this result. What we want is the center most intense part of our beam, so how do we find the center? With the iris positioned facing the beams propagation direction and the aperture is closed so that only a $1/3^{\text{rd}}$ of the beam total diameter can pass

through. A power meter that measures the average power of the beam is placed behind the iris aperture opening. Then the beam's diameter is swept across the aperture's opening until the meter reads the largest power value. This is repeated for smaller and smaller openings of the iris aperture until the highest output power is found, and there is no difference in power measurements for small sweep distances. This highly intense area is then treated as the center of the beam and is used to create the Fraunhofer diffraction pattern. The Airy disk appears as a bright central spot surrounded by concentric rings on the CCD camera's display (Fig 3.2). The smaller you make the iris aperture, the smaller the central spot will appear and the concentric rings will appear smaller and dimmer (Fig 3.3). The CCD camera is not looking directly at the beam; although reduced in size, the beam is still too intense for the CCD camera to view it. So, two neutral density (ND) filters were used; the first filter is an ND2 and the second filter is an ND3, together being equivalent to an ND5. At times it was useful to use a variable ND filter if the brightness of the beam was still too large for the CCD camera.



Figure 3.2 Airy disk diffraction pattern after first iris.



Figure 3.3 Airy disk diffraction pattern after second iris.

In the interferometer setup, the first mirror is the most difficult. This is because not only do you need the beam to follow the straight line that is measured from the south side of the board, but you need to get the center of the beam through both apertures, and the mirror (M1) is translating the direction of the beam propagation from vertical to horizontal, but also the mount moves the mirror in the y - z plane of the table. Furthermore, because of the way the mirror mount is connected to the post from the table, its position can be altered with only a slight movement of either control knobs on the optic. Thus, two table mounts must be connected to the same optical mount to increase stability, which then reduces the ability to move the mount easily to correct its position. The first step in the experimental process is shown in the figure below (Fig 3.4). The beam is reflected off the first mirror (M1), passes through two irides (I) and the alignment is verified using a CCD camera (CCD).

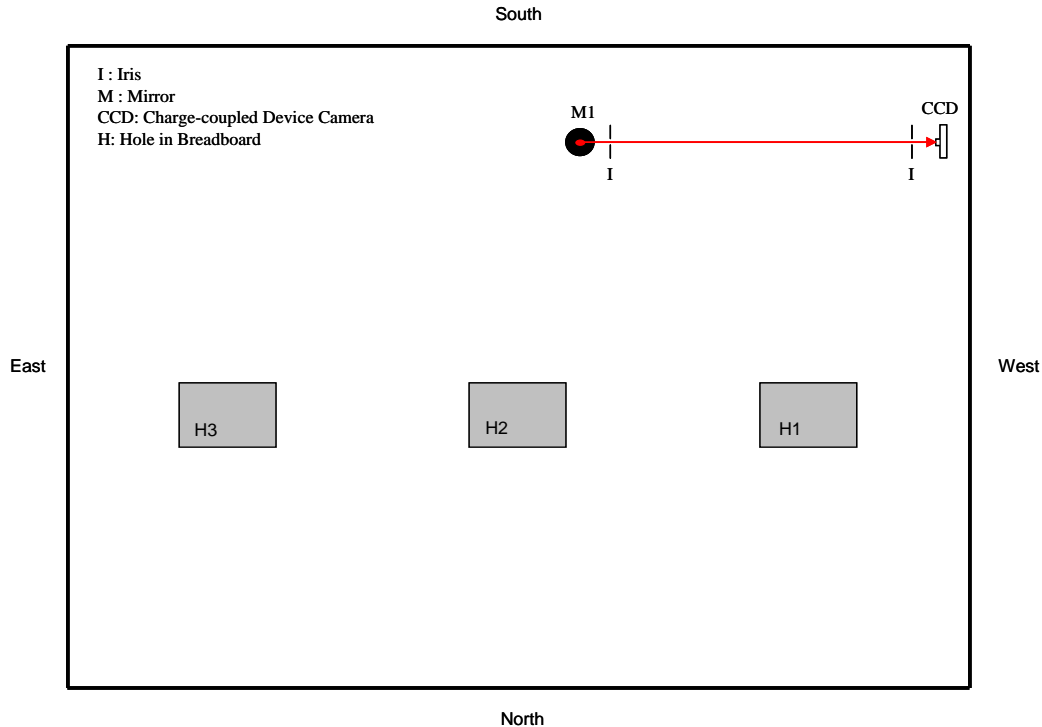


Figure 3.4 Alignment of the first mirror after beam exits the transport line.

Once the alignment of the first mirror is complete, it becomes clear why there is an $1/8^{\text{th}}$ of an inch spacer between the 4" post and the irides. The mirrors that are used throughout the experimental setup are each 1" Thorlab silver mirror ($\lambda/10$), and the optical mounts are Thorlab kinematic mirror mounts (KM100). When a kinematic mirror mount is attached to a 4" pedestal pillar post, a beam that passes through the center of our iris reflects directly off the center of the mirror in the kinematic mount. This helps the experiment greatly, in that it reduces the amount of effort needed to adjust the z-axis. So the next step is to align the laser along the holes in the breadboard to make our alignment easier. But, from where the beam is now, we cannot place the mirror mount over any hole because we are approximately 8cm from the edge of the table and that doesn't correspond to any hole on the x-axis (here the x-axis is from east to west, and the y-axis is from north to south). But, we can align the next set of mirrors along holes running along the y-axis of the table. So first the irides are put in place, along the y-axis, and the second mirror (M2) in our setup, needs to be aligned such that the beam passes through the first iris. Then, once that iris has been fully reduced, we need to traverse the second iris, where in each time the diffraction pattern is used as a guide. This part of the setup becomes our first straight line, but

what we need are two straight lines. You might be wondering why the first mirror doesn't create the first straight line in our setup and the second mirror create our second straight line. The answer to this, is that the first mirror is far too touchy to deal with. Although it is mounted with two mounts, the difficulty in aligning that mirror takes too much effort. So I prefer to leave that mirror alone and if your alignment with second mirror is done well, then all you need to do is bring the beam down the transport line in the same manner as it was during the setup and you should have no trouble get the beam to move through the two alignment irides. If there are difficulties, then a fine adjustment to the second mirror (M2) should be adequate or in a severe case the first mirror may need a small adjustment. Once you have aligned the setup for the second mirror (M2), none of these components should be moved. The irides should remain where they are along with the mount for the CCD camera. For this shall be the basis for all further alignment throughout the interferometer setup (Fig 3.5).

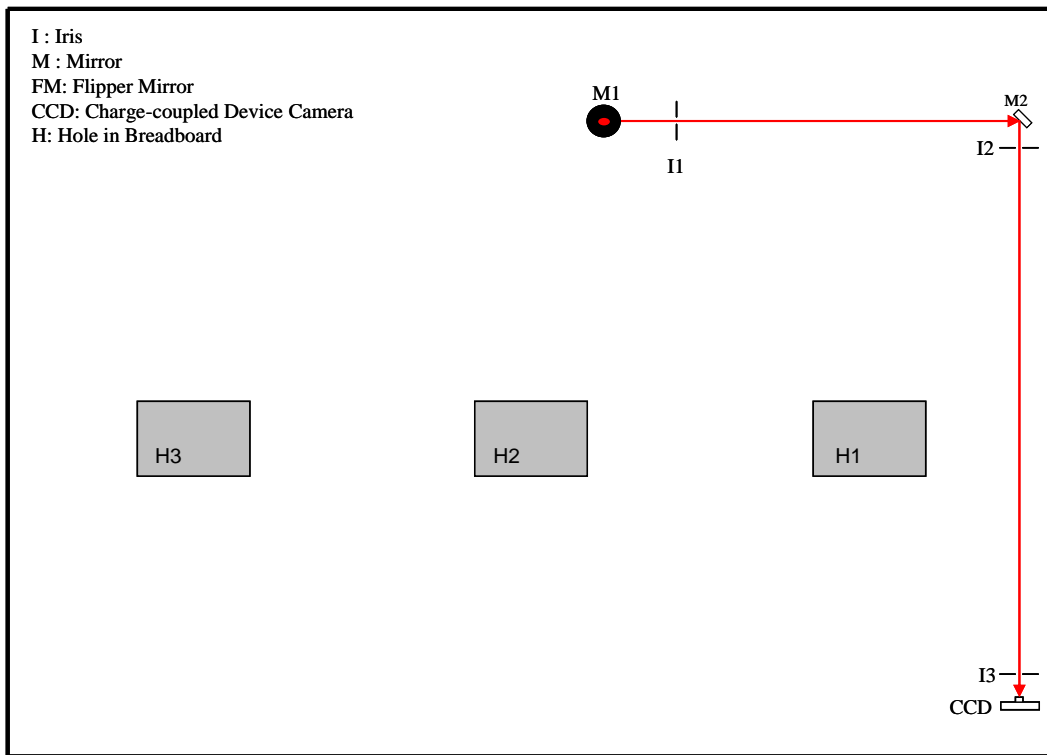


Figure 3.5 First straight line in interferometer.

So now we have one straight line, and the importance of this straight line is that when we put out next optical element in the setup, the beam will always strike that optical element in the

same place. This is the essence of reproducing this experiment, that the beam from this point on is the same. But we need one more straight line before the beam can enter the interferometer setup. This is because we are going to use a flipper mirror to reflect the beam to our next optical elements. We are going to use a flipper mirror for our next optical element because when flipped down the beam will continue in a straight line through our two irides and the beam can be checked using our CCD camera to see if for some reason it has moved. And the reason we need to check that this mirror is producing a straight line is because anytime the flipper mirror is flipped up or down its alignment shifts a little, and without being able to correct this shift, the experiment cannot obtain reproducible results. So again, two irides need to be placed in a straight line so that when the beam strikes the next mirror it will be located in the exact same spot every time. The problem for this straight line is that the original configuration for this experiment was to incorporate the other experiments that take place on this same breadboard. Therefore, this straight line needed to be directly over the Magneto Optical Trap (MOT) of rubidium atoms. The problem with that is the atoms in the MOT aren't located below a line of holes in the table, so a straight line that went directly over the MOT had to be found. The easiest way to reference where the MOT would be located would be to use the known position of one of the trapping laser for the MOT. A mirror that retro-reflects one of our trapping laser is located on the very breadboard that the interferometer is built on. During the retro-reflection, our trapping laser comes up through the trapping chamber and is reflected back down into the trapping chamber providing a beam that can be seen since the beam of the trapping laser lies in the visible spectrum. A measurement from the side of the breadboard can be made with a ruler to find what the distance the beam is from the side of the breadboard and hence the distance the MOT is from the side of the breadboard. This distance was measured to be ##cm. Then this same distance was measured on both ends of the breadboard and marked so that a line could be drawn from one end of the breadboard to the other. This provided a straight line for the two irides to be aligned to. Again, a CDD camera was used to check that the diffraction patterns lined up. This setup was also not to be moved once setup so that a quick check could be done at the beginning of the experiment. The two mirrors that had to be critically aligned in each case are the second mirror (M2) and the first flipper mirror (FM1) (Fig 3.6).

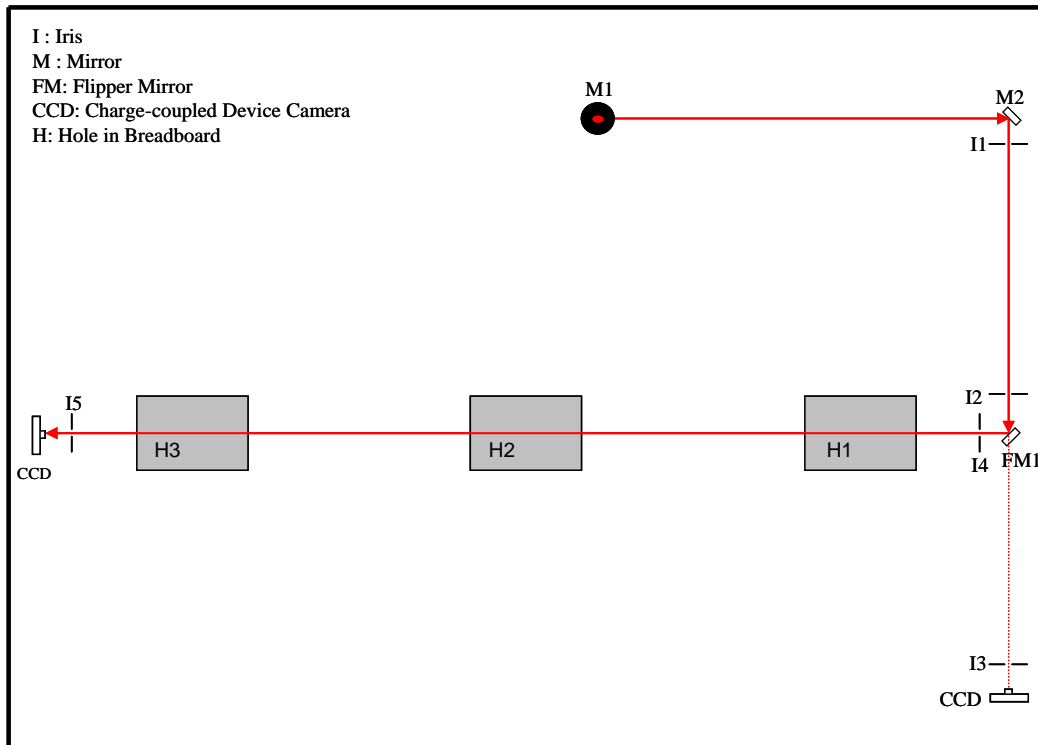


Figure 3.6 Interferometer setup for first flipper mirror.

Aligning these mirrors properly is what directs the beam through each set of irides. Since the most intense part of the beam was found right after the first mirror in the setup, that iris can stay closed and that should ensure that the part of the beam you are using throughout the rest of the setup is the part of the beam which is most intense. This helps a great deal, because you won't need to use the power meter during each step in the experiment. But, something to notice is that when securing a pedestal pillar post to the breadboard with a clamping fork, the alignment before securing the post down is not the same as after it is secured down; when using two 0.8mm diffraction spots for your alignment, this can cause a lot of grief. Typically, the shift from clamping down the post, was from left to right and could be compensated for by aiming the beam a little off center to the left of the aperture opening. Getting the beam through the first aperture opening was the easier part, but aligning the beam through the second aperture was the tricky part. Again, the z-axis of the beam never really moved, so it was only the x-y direction of the breadboard that needed to be considered. But what we were really trying to produce were perfect right angles that would reflect the beam in straight lines (Fig 3.7). So it really was a matter of getting the right depth to reflect the beam during its propagation. Once you have the

alignment close so that the diffraction pattern of the first iris on the CCD camera appeared to overlap the diffraction pattern of the second iris on the CCD camera, finger movement would be too severe for the alignment of the beam. At this point small controlled taps using any instrument could nudge the post the minimal distance it needs to be moved to find the correct alignment. After each tap the post would need to be secured down again using a clamping fork before the control knobs on the optical mount could be adjusted to see if that movement was sufficient. This same process is needed for every mirror on the breadboard, including those on the translation stage.

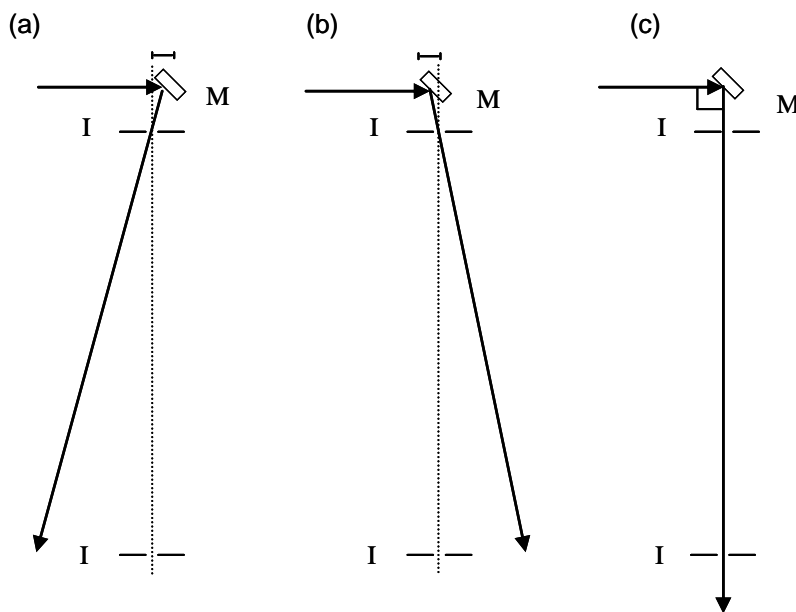


Figure 3.7 (a) Reflection angle is less than 90 degree, (b) greater than 90 degree, (c) exactly 90 degrees.

The third mirror in our setup is another flipper mirror (FM2), this is the mirror that when flipped down allows the beam to pass through the permanent setup for our second straight line, and when flipped up directs the beam through our interferometer setup. Again we go through the same process of securing the irides along a line of holes in the breadboard and checking their alignment using a CCD camera (Fig 3.8). From this point on, all beams will follow a set of holes across the breadboard. This mirror also represents a point in the construction of the interferometer where no mistakes can occur beyond this point. That is because once the mirror (FM2) is set in its position and the two alignment irides along with the CCD camera are moved

to the next alignment position, there is no point of reference that can be used to check if anything has moved during the period of time that elapses between mirror alignments. Unfortunately, this will be the case every time the movable irides (I-M) along with the CCD camera are moved from one location to the next. These flipper mirrors are a necessity to the experimental setup but are also very unstable, and if something were to fall on the breadboard or bump the breadboard, the adjustment screws that are used to directionally control the beam will move ever so slightly and change your alignment. Since our setup uses two of these mounts, you must check them both. Also, since you are checking the alignment by flipping down the second flipper mirror (FM2), it will change the orientation of that mirror, and that means unless everything was setup up exactly for the next mirror or the following mirror(s), you must go back and repeat the alignment for the second flipper mirror (FM2). This means everything downstream of that mirror will have changed, and that means you will need to re-setup each optical element down stream of that mirror, which could mean repeating many hours of work.

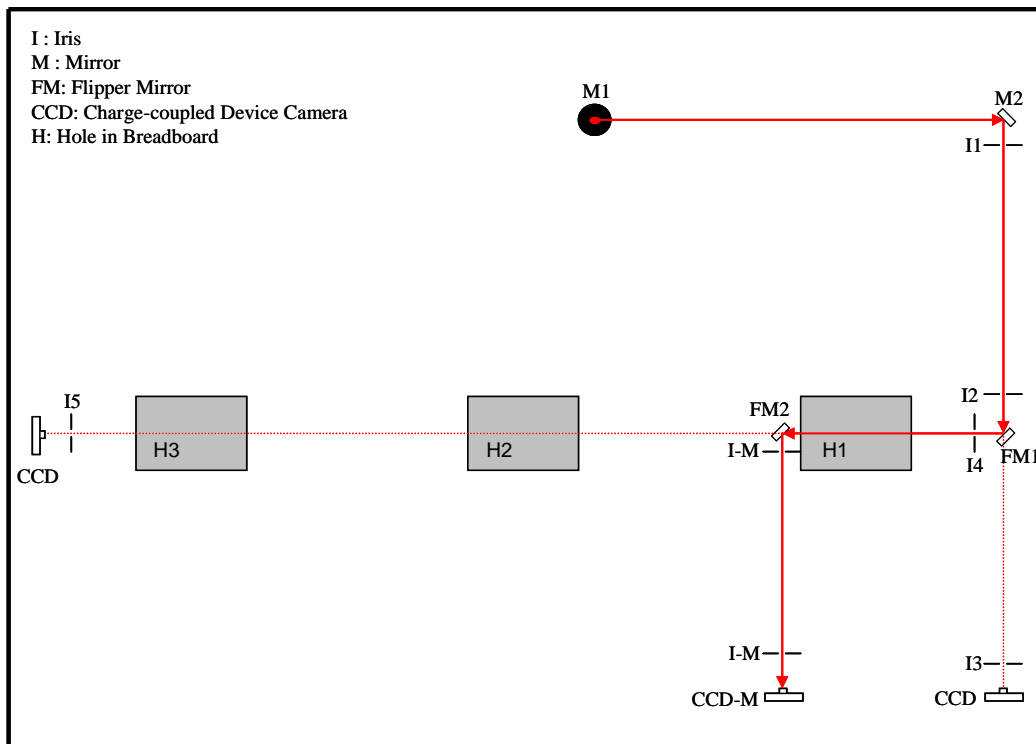


Figure 3.8 Alignment of second flipper mirror.

The next mirror in our setup is mirror three (M3); the alignment for this mirror is straight forward. The beam is reflected at a 90 degree angle from its direction of propagation and aligned over a set of holes. This mirror reflects the beam to one of our two 1" 50% beam splitters, but the alignment is to be done prior to the beam splitter being introduced is the beam line.

The next step is to place the beam splitter into the beam line. Once this is done the beam splitter will reflect one portion of the beam to a mirror on a translation stage (TS1), and the rest of the beam will pass through the beam splitter to a mirror on another translation stage (TS2). The beam being reflected to the first translation stage (TS1) should be aligned over a set of holes (Fig 3.9). However, in this case because there is so little room to get all the optical elements on the table, the CCD camera will need to be mounted via an extension piece that extends off the table (Fig 3.10). The beam that passes through the beam splitter will be refracted and no longer follow a straight path.

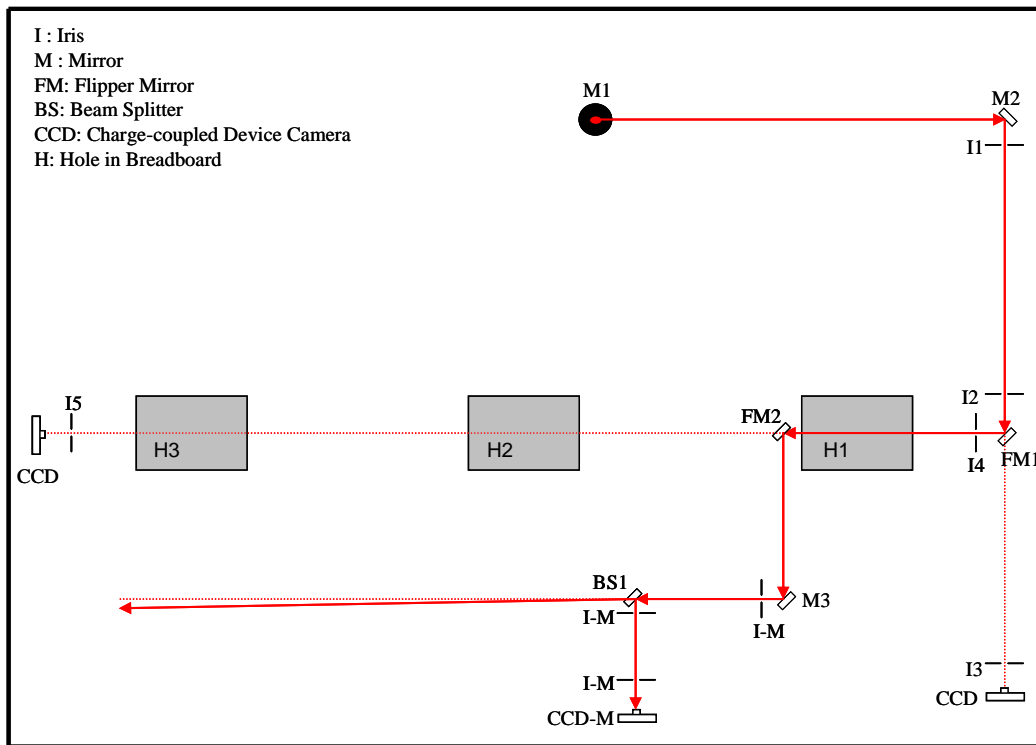


Figure 3.9 Alignment of first beam splitter.

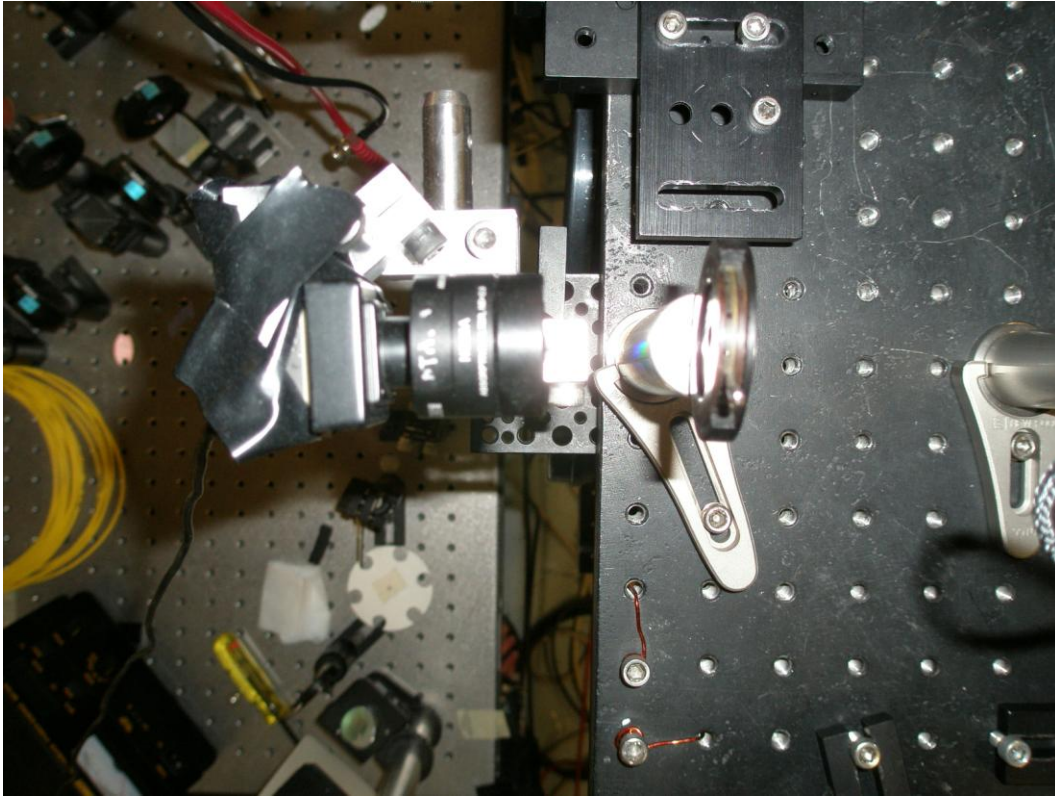


Figure 3.10 Photograph of extension plate allowing the CCD camera to be mounted off the experimental table.

The setup of the first translation stage (TS1) is much different than the setup of the second translation stage (TS2). This is because there is a hole in the breadboard (H2) that the beam needs to be reflected around so that the optical elements on the board can be positioned in the beam line. This means that the mirrors on this translation stage (TS1), (M4 and M5), will make use of extension pieces. When screwing down the extension plates the shortest screws possible for the job need to be used or the screw will go too far into the stage and cause it to not translate. This becomes especially important on the second stage where there are no extension plates, and therefore positioning and screwing in an optical mount only to find it must be unscrewed and hence the position will change. Therefore, checking the mounts with the screws ahead of time becomes critical. Positioning of mirror four (M4) should then be straight forward where the beam is aligned over a set of holes. This task becomes somewhat easier because the y-axis of the breadboard (north-south direction) can be controlled by moving the translation stage rather than the mount to create the straight line needed. The mirrors on the translation stages do

not make use of pillar posts, they make use of 2” post holders; with 2” posts connected to kinematic mirror mounts. To make alignment easier, slip-on collars can be used to fixed the height (z-axis) of the mirror. Once the alignment of mirror four (M4) is accomplished, mirror five (M5) can be place in the beam line. Mirror five (M5) is probably the most difficult mirror to align since it makes use of a pedestal base adapter and an extension plate. Because when we tighten down this mirror with a post clamp it changes the alignment of the mirror, a breadboard clamp was used to secure the post clamp down before tightening the post clamp (Fig 3.11). This prevented the post clamp from changing the orientation of the mirror. The alignment for mirror five (M5) will again be down a set of holes, and this set of holes needed to be chosen so that there is clearance for the “glass cell with heating apparatus” device. Placing the glass cell and heating apparatus on the breadboard will show you which set of holes are most logical. Once mirror five (M5) is aligned it will not be changed throughout the experiment.

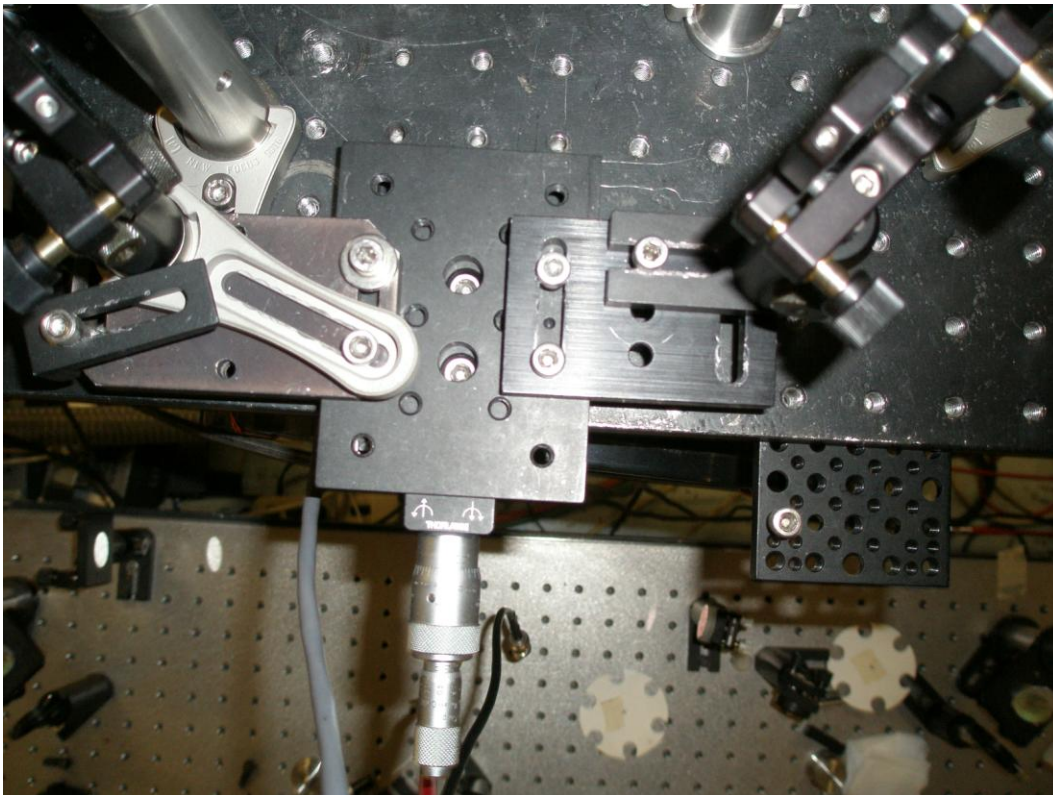


Figure 3.11 Photograph of the first translation stage with optics mounted on their extension plates.

At this point the first translation stage (TS1) needs to be, if it has not already been, brought into a position where the differential micrometer has not extended its piston any distance. The reason we want the differential micrometer in this position is because we are going to replace it with a DC servo actuator, and the actuator doesn't have a large travel range. Once the translation stage is in this position, the distance the beam travels from the first beam splitter (BS1) to the fourth mirror (M4), from mirror four (M4) to mirror five (M5), and the distance from mirror five (M5) to the second beam splitter (BS2), need to be measured, even though the second beam splitter is not aligned yet. This can then be used as a basis for the distance that the beam needs to travel through the optical elements on the second translation stage. To get the desired result, we need two phase matched pulses, that overlap in time. This means that their path length through the interferometer must also be nearly equal. This point in the setup is where you can finally breathe easy, because you have reached the end of the path of the beam (Fig 3.12). As long as you leave the two irides in their final positions, this is the first place you can check to see if something in your setup has moved. If you check this position and the beam is no longer lined up, you need to flip down the first flipper mirror (FM1) and check your first straight line. If your first straight line is not aligned, then you know you have a problem upstream, most likely from the KLS room and you need to check your experiment. If the beam is okay, or after you have realigned the beam from upstream, then because you had to flip down the first flipper mirror (FM1), the alignment has certainly changed. But the good news is the beam is still hitting that mirror exactly where it was before, so by simply rotating the adjustment screws the beam should go through the permanent irides and to the CCD camera easily. To have done this though, the second flipper mirror (FM2) would have needed to be flipped down, so again, its alignment will have changed. Now by moving the CCD camera to its final location, a simple turn of the adjustment screws should get you back to that point also, meaning the beam is perfectly aligned again through your interferometer. This will also let you know whether anything else more serious has happened to your experiment, because you will not be able to get the beam to that final spot if something after the second flipper mirror has moved.

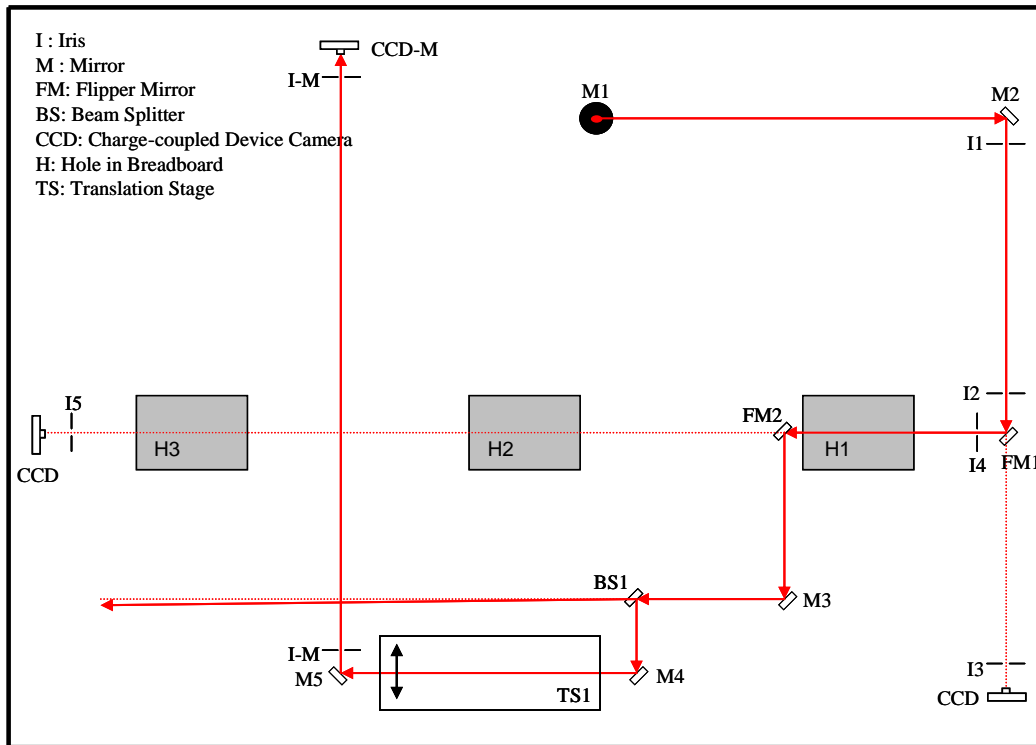


Figure 3.12 Point in experiment where the final alignment position is located.

Now we have a beam that has been refracted from the first beam splitter and it's approaching our sixth mirror (M6) which is positioned directly on the second translation stage. Using the holes again, line up a set of irides and the CCD camera so that a straight line can be formed. Again, because you can use the translation stage, the alignment along the x-axis of the board (east-west direction), should be simplified and the use of slip-on collars will reduce z-axis management. The seventh mirror (M7) is again a tricky mirror, this is because we are again trying to align the beam along a set of holes. But now the beam is traveling across the breadboard through the interferometer set up and many optical elements may create obstacles that need to be navigated through. Being careful and patient will save you a lot of time at this point since a bump of any mirror may make non-rechangeable changes to the alignment. Once the second translation stage (TS2) is setup, it will no longer move afterwards. As we see (Fig. 3.13), as the second translation stage moves in our setup, it actually changes the position of the beam on the second beam splitter.

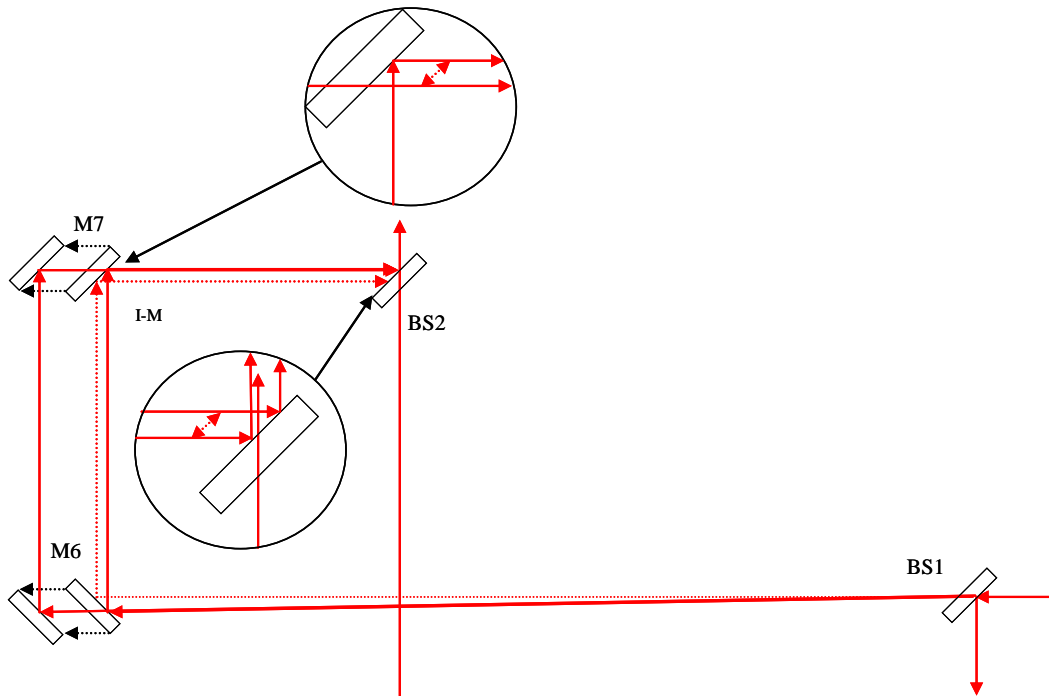


Figure 3.13 Detailed picture of how the refracted beam from the first beam splitter causes its alignment to change on the second beam splitter if the translation stage is moved.

Now it is time to put the final optical element into our interferometer. That is the second beam splitter (BS2). After first checking the beam coming from the first translation stage (TS1), is still a straight line, we then insert the second beam splitter (BS2). This is going to change the direction of the beam from the first translation stage slightly, like it did after the first beam splitter (BS1). Here we want to use the beam from the second translation stage to get through two irides again, one placed right after the second beam splitter (BS2), and the second iris that was used for the beam from the first translation stage (TS1). You will also need to block the beam coming from the first translation stage, so the two are not confused. Once you have gotten the beam close to being aligned, you need to measure the distance in each leg of the interferometer again to make sure the beam in the second leg of the interferometer (that's the second translation stage (TS2)) is equal to the first leg (TS1). Once you've adjusted the second translation stage (TS2) to match the first (TS1), now it's time to make you're final alignment of the beam splitter, so that the beam from the second translation stage (TS2) goes through both irides and ends up on the CCD camera perfectly (Fig 3.14). Again this adjust requires more precision than can be achieved by your fingers. So slight tapping of the base of the beam splitter

post will be needed to bring the beam splitter into its final alignment. Now, after unblocking the beam from the first translation stage (TS1), you can use the adjustment screws on the beam splitter's optical mount to bring the two beams into alignment. This alignment will not go through the centers of the previously aligned irides. The best way to find the proper alignment is to lengthen the beam as far as possible from the beam splitter. When the beam travels a farther distance, it is easier to tell how good the overlap is. Once the beams have been sufficiently overlapped, it's time to put the beams back on the CCD camera to see if any interference patterns can be discerned. If there are enough vibrations on the table or with the beam, the inference fringes will become apparent quickly. Otherwise you will need to manually move the first translation stage through its distance until the location where the two pulses overlap and produce interference fringes. If the second translation stage is moved, then the beam will wander on the the beam splitter and the alignment will be lost.

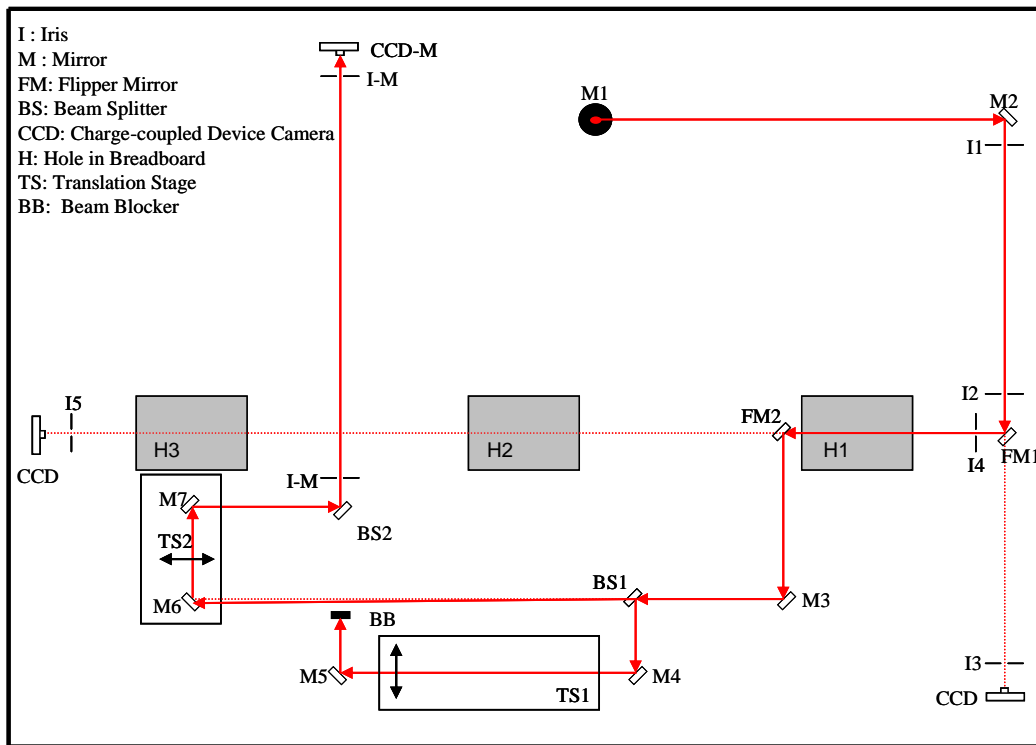


Figure 3.14 Alignment of the second beam splitter.

Once the interference fringes are witnessed, the iris should be placed along the beams propagation, and aligned so that the irides are along its propagation. This time you are not

aligning the beam to the iris; you are aligning the iris to the beam (Fig 3.15). Once the irides are in place, this is now your new location for checking if the experiment has changed anywhere upstream.

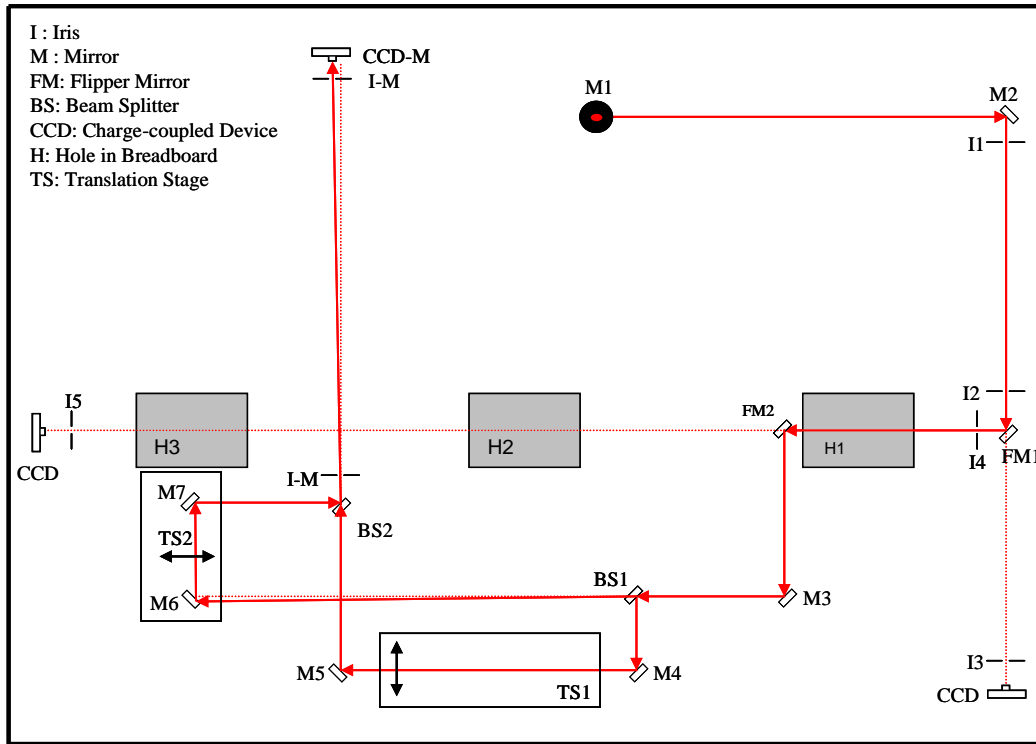


Figure 3.15 Final setup for interferometer.

Now the heated rubidium cell can be put in place along with the photomultiplier tube. As the two pulses travel through the rubidium cell, each pulse has some probability of exciting an atom. If an atom is excited by the first pulse, because of the path difference of the two pulses, the second pulse will arrive a moment later. This moment allows the atoms wavefunction to evolve before being excited by the second pulse. Once the second pulse excites that same atom, it will end up in a final target state. This target state is the $5d_{3/2}$ state, when the atom decays from that it, it decays down into the $6p_{1/2}$ state, when the atom decays from this state to the ground state, it releases a 420 nm photon. To detect these 420 nm photons, we use a photomultiplier tube that makes us of a blue filter that blocks all other photons from being seen by the photomultiplier tube. These decay photons cause the photomultiplier tuber to produce a current. This current then corresponds to channel of the output of the photomultiplier tube, and these

channels correspond to a distance in path length of the two legs of the interferometer. A labview program was written that controls the motorized DC servo actuator, so that for each step of the servo motor a corresponding channel will be recorded from the photomultiplier tube. From this information we can tell for what path length do we get more excitations, and these excitations should correspond to the probabilities of actually exciting atoms into these states. The information we receive should be oscillations in the signal corresponding to the energy difference between atomic levels. The data acquisition program will step one arm of the interferometer through a length of 83 picoseconds (25 mm) with each step being 220 attoseconds (0.05 μm) via motorized actuator (DC servo motor).

CHAPTER 4 - Conclusion & Further Considerations

In this report, I describe the theory and setting up of an apparatus for a pump-probe experiment. The goal was to get a working device, to see the interferogram from the Mach-Zehnder interferometer, and to observe the beat note from the $5p_{1/2}$ - $5p_{3/2}$ fine structure splitting. I was successful in setting up a robust interferometer, in working through the theory, and in observing the interferogram. Unfortunately, I was disappointed in not seeing the beat note.

When the experiment was initially conceived, test experiments were conducted to see if the laser beam and other apparatus would be sufficient to conduct the experiment. When the beam was tested to see if it had adequate power to conduct the experiment, the full beam was used, meaning that a very small amount of the beam was lost due to reflections, and the amount lost due to beam splitters and irides were not compensated for. This test also included the use of a Magneto Optical Trap (MOT), which cools and traps Rubidium atoms into a small dense spot. As the beam was directed onto this dense target of atoms, the beam was also focused down to the exact spot where these atoms were located. These conditions, though, were ideal; the way that the experiment was conducted did not have such ideal conditions. When the beam was directed into the cell, the beam was not focused. Focusing the beam into the cell should increase the excitation rate. These drawbacks caused no signal to be detected during the experiment. If the power of the oscillator laser could be increased, then the experiment should be able to be conducted since all the other properties of the experiment were witnessed.

This project not only took planning, but hard work and time. The planning involved researching interferometers and deciding which optical elements were needed and to what specifications, building many to scale models of the setup and testing their viability, testing experimental conditions to see if they would produce the desired results, and reading research papers to see what else has been done and how it can be applied to our experiment. The hard work involved setting up the experiment numerous times, each time finding out something new and realizing that if done differently, they could improve the entire experiment. While at the same time I was working through hours theoretical calculation discovering what type of data we expected to see.

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